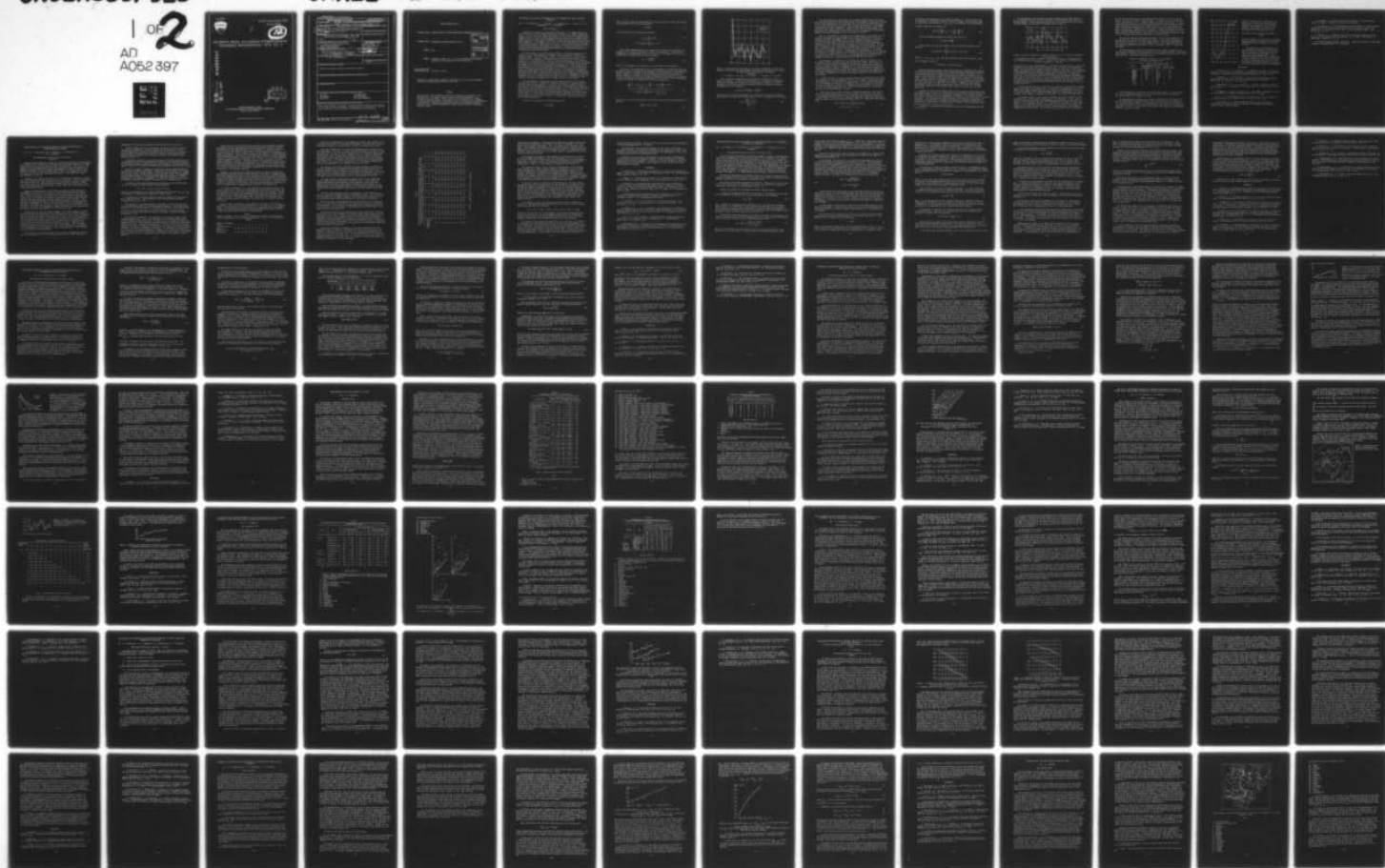AD-A052 397

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This report contains 13 articles by various Russian authors on the subjects
of ice jams and ice forecasting. Characteristics of ice conditions and how
these conditions lead to problems in forecasting are discussed.

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NOTICE

THE TEMPORAL AND SPATIAL CHANGEABILITY OF ICE PHENOMENA AND THEIR LONG-TERM FORECASTS

By: T. N. Makarevich, Z. A. Yefimova, V. A. Rumyantsev, L. K. Savina, R. Ya. Alekseyenko, S. V. Shanochkin

(GGI, Leningrad)

Recently, the practice of long-term forecasting of ice regime elements of rivers has come to include physico-statistical methods to a greater and greater extent. One of these most widely used methods is the method of forecasting the characteristics of the ice regime according to the data fields of meteorological elements with the preliminary arrangement of these fields on the natural orthogonal components - this began to be used in 1968 at the Hydrometeorological Center of the USSR (8), and somewhat later in GGI (3). At the same time, the accuracy of long-term forecasts, particularly for rarely repeated years, remains as before far from satisfying the requirements of questions. Further research into the possibilities of perfecting the existing methods and finding new approaches to solving this problem are necessary.

For this purpose, the authors made a detailed statistical analysis of the longest series of observations of elements of the ice regime on rivers with different types of ice formations: stable - the northern area rivers (56 monitoring stations), unstable - the Danube River (20 monitoring stations), and transitional - the Transbaltic Rivers (27 monitoring stations). By statistical analysis of the temporal series, one means in this case evaluating and duplicating the properties of the initiating process which lies at the basis of the series according to the available realizations of characteristics. The usefulness of such analysis, if it is of course carried out correctly, consists in the possibility of identifying general principles to which all or part of the temporal series are subordinate. The next stage consists in the attempt to explain these principles and to find possibilities of using them for the purpose of prediction. Knowledge of the basic properties of the temporal series - changeability and the characteristics of its periodic fluctuations - aid one in solving the primary problem - predicting the behavior of a temporal series in the future.

The successfulness of employing the most modern methods of statistically analyzing time series - spectral and correlation analyses - depends chiefly on the care taken in selecting data. In order to use the structural features of time series of the observations of characteristics of ice phenomena subsequently, one should be certain that such series are steady, or, in other words, that their basic statistical parameters do not significantly change in the course of a certain period of time. When plotting the forecast diagrams, an objective check of the series for steadiness has not been nearly carried out up to this point, which could not fail to have an effect on the results of employing some particular forecasting methods.

A check of the steadiness of the mean value of $\tilde{x}$

$$\tilde{x} = \frac{1}{n} \sum_{j=1}^{n} x_j,$$

(1)

where x_j is the value of the time series at the j-th moment in time, was carried out according to the following criterion

$$\alpha = \frac{s^2}{s_1^2};$$

(2)

here s^2 and s_1^2 are the dispersion estimates:

$$s^2 = \frac{1}{n} \sum_{j=1}^{n} \left(x_j - \tilde{x} \right)^2,$$

(3)

$$s_1^2 = \frac{1}{2(n-1)} \sum_{j=1}^{n-1} (x_{j+1} - x_j)^2.$$

The slowly changing trend in the average value leads to an overage in the estimate of s^2 and has practically no effect on the value s_1^2. The series is recognized as a steady-state series in relation to the average value if the calculated value of α falls into the critical region

$$\alpha > 1 - \frac{t_q \sqrt{n-2}}{n-1},$$

(4)

where n is the length of the series, t_q is the quantil of the normal law.

A check on the steady-state nature of dispersions and correlation functions was made by means of comparing the estimates of dispersion and the autocorrelation function obtained according to the components of the successively shortening series (Figure 1). In order to give an objective answer to the question of whether differences between the selected estimates are significant, with respect to those obtained by the separate components of the series, one uses the Bartlett criterion in the case of dispersion (6), based on statistics

$$\frac{\sum_{i=1}^{N} (n_i - 1) \ln \left(\frac{1}{\sum_{i=1}^{N} (n_i - 1)} \sum_{i=1}^{N} (n_i - 1) s_i^2 \right) - \sum_{i=1}^{N} (n_i - 1) \ln s_i^2}{1 + \frac{1}{3(n_i - 1)} \left(\sum_{i=1}^{N} \frac{1}{n_i - 1} - \frac{1}{\sum_{i=1}^{N} (n_i - 1)} \right)},$$

(5)

while in the case of the intraseries correlation function the following statistic was used

$$\sum_{i=1}^{N} (n_i - 3) \left[z_{i(k)} - \tilde{z}_{(k)} \right]^2.$$
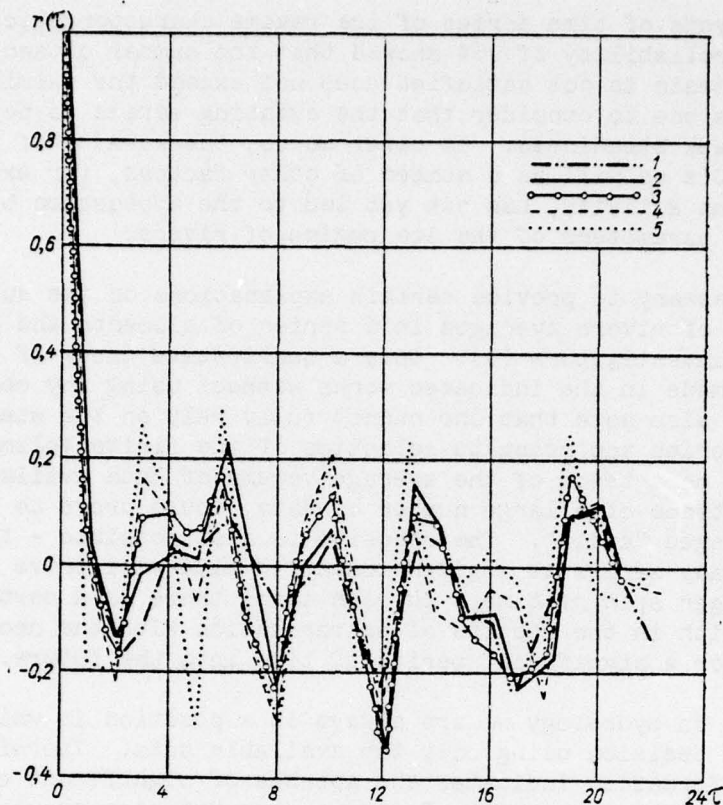
(6)

- 2 -

Figure 1. Autocorrelation functions of the times of appearance of ice on the Severnaya Dvina River and near Medvedka monitoring station plotted for the entire series and its successively shortening components.

1 - 70 years, 2 - 60 years, 3 - 50 years, 4 - 40 years, 5 - 30 years.

Both statistical components are approximately distributed as χ^2 c N - 1 degrees of freedom. In the cited expressions, N is the number of components into which the series is divided; n_i is the number of members in the i-th component of the series; s_i^2 is the selected estimate of dispersion obtained according to the i-th component;

$$z_{i(k)} = 1,15 \lg \frac{1 + r_{i(k)}}{1 - r_{i(k)}} + \frac{r_{i(k)}}{2(n_i - 1)}, \tag{7}$$

where $r_{i(k)}$ is the selected estimate of the intraseries correlation function upon a shift by k units, obtained according to the i-th component of the series:

$$\widetilde{z}_{(k)} = \frac{\sum\limits_{i=1}^{N} (n_i - 3) z_{i(k)}}{\sum\limits_{i=1}^{N} (n_i - 3)}. \tag{8}$$

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The cited analysis of time series of ice regime characteristics of rivers with a probability reliability of 95% showed that the number of sections according to which this hypothesis is not satisfied does not exceed the permissible value of 5%. This enables one to consider that the existing series do not contradict the hypothesis of weak steadiness. In other words, the warming of the climate observed in the 1930's as well as a number of other factors, for example, the growing role of human activity, has not yet led to the appearance of significant trends in the basic parameters of the ice regime of rivers.

Here it is necessary to provide certain explanations on the subject of the unsteady ice regime of rivers averaged in a series of elements and observed earlier by certain investigators (9). Only a qualitative check of the series for steadiness was made in the indicated works without using any objective criteria. We shall also note that one cannot fully rely on the steadiness or unsteadiness of a series according to selection of the finite volume. The fact that it appeared to be a trend of the average volume of data available at that time, with the existence of a large number of data, could prove to be simply a branch of a prolonged "cycle". The opposite is also possible - the series that seem to be steady series at a given moment in time will prove to be unsteady in a different, longer span of time. In both cases there is a certain danger of placing too much faith in the results of extrapolation with the necessity of making a decision for a significant period of time into the future.

Unfortunately, in hydrology we are always in a position in which it is necessary to make a decision using only the available data. Therefore, if all of the available information indicates the absence of significant changes in series of elements of the ice regime of rivers, our decision should recognize the steady-state as reality. Consequently, we have every basis to employ different statistical methods not only with respect to an individual component of the series, beginning in the 1930's, but also with respect to the entire series as a whole, including earlier years, which makes their very application more well-founded.

A typical feature of a quite long time series of observations of a certain characteristic of the ice regime of rivers is the presence of prolonged irregular fluctuations. By studying these fluctuations, one can conclude that they can be represented as the total of somewhat more or less regular fluctuations. In order to study this "mixture" of regularity and irregularity in the series of river ice regime characteristics, spectral analysis provides the natural approach from the mathematical viewpoint.

There exist many problems related to obtaining estimates of the spectra and of the themes chiefly due to a certain extent to the obvious fact that it is not always possible satisfactorily to describe the infinite set when only a finite number of data is given. However, today fully suitable methods have been developed for estimating spectral density $\hat{f}(\omega_j)$. These have the following form

$$\hat{f}(\omega_j) = \frac{1}{2\pi} \left\{ \lambda_0 R_{(0)} + 2 \sum_{k=1}^{m} \lambda_k R_{(k)} \cos \omega_j k \right\}. \tag{9}$$

$$\omega_j = \frac{\pi j}{m}, \; j = 0, 1, \ldots, m,$$

and are only distinguished by the choice of weights λ_k. Here m is the point of truncation or the maximum number of employed changes, conventionally taken at random from the condition $m < \dfrac{(n)}{3}$; $R_{(k)}$ is the estimate of the covariation function taken upon the change in k:

$$R_{(k)} = \frac{1}{n} \left\{ \sum_{t=1}^{n-k} x_t x_{t+k} - \frac{1}{n} \sum_{t=1}^{n} x_t \sum_{t=1}^{n-k} x_t \right\}. \tag{10}$$

The T'yuka-Khening estimate was used in the work (10)

$$\lambda_k = \frac{1}{2} \left[1 + \cos\frac{\pi k}{m} \right]. \tag{11}$$

As the result of this, we initially obtain the rough estimates of the spectrum

$$L_j = \frac{1}{2\pi} \left(R_{(0)} + 2 \sum_{k=1}^{m-1} R_{(k)} \cos\frac{\pi k j}{m} + R_{(m)} \cos\pi_j \right), \tag{12}$$

where $L_{-1} = L_{+1}$, $L_{m-1} = L_{m+1}$, and then by means of smoothing we shift to the final estimates of $f(\omega_j)$

$$\hat{f}(\omega_j) = 0.25 L_{j-1} + 0.50 L_j + 0.25 L_{j+1}. \tag{13}$$

Spectral analysis provides a quite crude method of determining the reality of cycles by identifying whether they introduce frequency bands that correspond to the cycles that make a contribution to the total series dispersion; it is crude in the sense that a precise establishment of this fact requires that the length of the series be at least 7 times longer than the length of the longest cycle. Hence, in order to determine, for example, the verity of a 22-year cycle, one should have data for a minimum of 150 years, while to determine the verity for an 11-year cycle one needs data for 80 years. Inasmuch as the reliable hydrological series are usually much shorter, then it is clear that tasking such cycles according to the separate series requires that we have more data than we do.

In order to obtain more reliable ideas about the reality of the long cycles, the single escape, to our view, consists in a joint spectral analysis carried out according to several series with subsequent averaging of the selected spectra for a group of rivers that are homogeneous with respect to the correlation (spectral) function[1]. When certain conditions of averaging are observed, the estimate is equivalent to an estimate of a spectrum which could be obtained according to a significantly larger number of members than the length of each individual series.

---

[1]A check of the intraseries correlation functions for homogeneity was made in a work (1).

In the process of the combined statistical analysis of the time series of the ice formation periods on rivers, covering a quite extensive territory with varying regimes, a latent quasi-cyclical nature was identified which can provide a certain effect when plotting the forecast links (Figure 2).
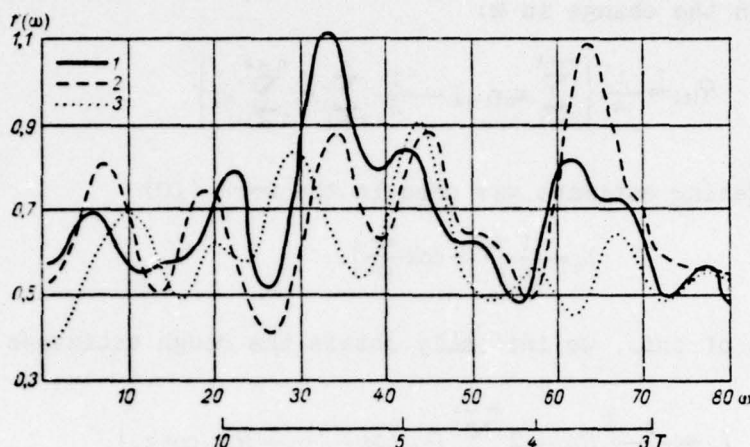

Figure 2. Selected estimates of spectral density $f(\omega)$ of the times of appearance of ice on rivers.
1 - Severnaya Dvina River - Abramkovo monitoring station, 2 - Vychegda River - Sol'vychegodsk monitoring station, 3 - Danube River - Budapest monitoring station (ω - frequency, T - period).

It should be noted that the character of this quasi cyclical nature is practically identical in all three rivers (the northern area, the Danube, the Transbaltic area). One can identify 11-year and 22-year cycles in the first series; certain differences pertain to the shorter cycles - the 5 and 7-year ones. The commonality of the identified cycles indicates a single global principle of their origin. Relative to the cycle which lasts approximately 11 years, one can confidently state that it has a solar nature (4, 7). According to geophysical investigations, the nature of the 22-year cycle is evidently associated with the variable sign of the magnetic field of two 11-year cycles, the even and odd; and in the meteorological processes the 22-year cycles frequently appear more noticeably than the 11-year cycles (5).

We shall examine the use of cyclicity for purposes of forecasting in greater detail applicable to the Danube River. An analysis of changeability of ice phenomena on the Danube demonstrated the most clearly pronounced 22-year cyclicity in the fluctuations of the length and onset times of ice phenomena; to a significantly lesser degree it appeared in the times of the river's freeing from ice.

An attempt is made in this study to estimate the possible effect of solar activity in its 22-year cycle on processes of ice formation. In this case, a method of analyzing cyclicity for hydrometeorological forecasts which was suggested by V. N. Kupetskiy was used (2). According to the table of "epoch application", by knowing three factors - the parity of the 11-year solar cycle, the phase (rise or fall) and the value of Wolf sunspot numbers, the correlation diagrams can be constructed. One can identify certain principles individually

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for the odd and even cycles in the diagrams in the form of direct and reverse links. The value of the Wolf sunspot number is assumed to be the actual value for the current year or for a forecast whose validity is quite high. In individual years the links are poorly expressed and therefore the forecast for them should not be made according to the submitted method. Such years include the years following the maximum of the 11-year cycle, before the minimum and the year of the minimum. Furthermore, in a number of cases the identified relationship is vaguely expressed due to the instability of characteristics of the ice regime and the limited nature of the series - the observations encompass a total of 3 or 4 22-year cycles, which hinders its statistical basis.

The authors compiled verification forecasts of the times of appearance of ice for years of the current 20-year cycle (1964 - 1971) during these years in the region of the even 14, 16, and 18-year cycles. There were unsatisfactory results from 8 years in 2 instances (1965 and 1968); in 6 cases the error did not exceed the permissible one and of these, in 5 cases it was 0 + 5 days (see the table).

One can anticipate phases of development of the Danube ice regime in up-coming years according to the prediction of the Wolf sunspot numbers. The authors have compiled a forecast of the length of the ice phenomena and the times of their onset for 1973 - 1974 which was fully valid.

Validity of Forecasts of Dates of the Appearance
of Ice on the Danube River

Year	Date of Appearance of Ice		
	According to Forecast	Actual	Error, days
1964-65	13/II	10/II	3
1965-66	15/XII	13/I	29
1966-67	9/I	14/I	5
1967-68	19/XII	16/XII	3
1968-69	16/I	24/XII	23
1969-70	6/I	24/XII	13
1970-71	18/I	14/I	4
1971-72	17/I	16/I	1
Norm		3/I	
δadd		13	
$P\%$		75	

Our investigations of the character of the relationship of solar activity with the ice phenomena showed that it is particularly clearly manifested in the extreme years, with respect to icing.

We shall examine an example of a similar relationship of the duration of the ice phenomena, the greatest assigned value (according to the Danube data) with the Wolf sunspot numbers in the current year. As is evident in Figure 3, the highest correlation coefficients characterize years whose ice phenomena are prolonged (over 35 - 40 years) and years with mild development of ice phenomena (duration less than 20 days).
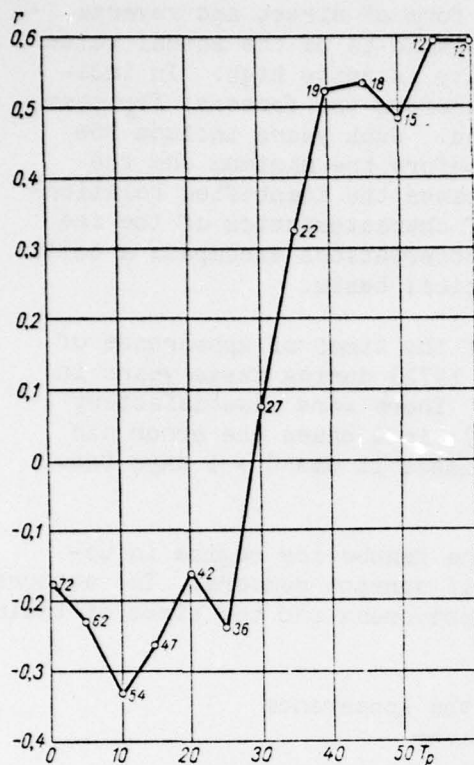
Figure 3. Relationship of correlation coefficients r between the duration of ice phenomena on the Danube River (Budapest - Mokhach), the highest set value T_p, and the Wolf sunspot number for January of the current year and the value of T_p.

The small circles indicate the number of years.

With the exception of cases near the average multiyear value of duration, the correlation coefficient sharply increases - from 0.32 to 0.58.

Investigation of the changeability of ice phenomena in comparison with cyclicity made it possible to obtain a certain idea about the tendency of development of ice conditions in succeeding years. It is naturally assumed that for this purpose data on solar activity could be used in addition to data on atmospheric circulation, and in this sense the reported results are viewed as the first stage of this kind of investigation.

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MODERN PRINCIPLES OF DEVELOPING METHODS OF LONG-TERM FORECASTING OF RIVER FREEZING AND THAWING

By: Ye. I. Savchenkova, Ye. S. Karakash, N. D. Yefremova, and
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During the development of a method of long-term forecasting of the appearance of floating ice, it is expedient to estimate when the autumn cooling of the water begins with a high degree of timeliness and how intensively it will occur. The course of water cooling depends in the final analysis on the development of atmospheric processes, and the frequency and intensity of waves of cold and heat. Nearly all methods of long-term forecasting of the times of appearance of ice are based on an analysis of atmospheric processes in the months that precede the appearance of the ice.

Attempts to use statistical methods for investigating atmospheric processes and their interrelationships have been made for a long time. Correlation analyses have usually been used. Many synoptic rules (the method of analogs, rhythms, etc.) that are used in long-term weather forecasts have been the result of the statistical generalization of materials. Still, their use in hydrology does not always provide good results.

Regional characteristics of the synoptic processes are used during the development of methods of ice forecasts. These characteristics well reflect the temperature of the air near the ground or its deviation from the normal value. Thus, for example, the duration of the western shift in November, which carries heat in the period of freezing of the upper and middle Volga, depends upon the developed temperature contrast between the sea and the land. This contrast is estimated according to the difference between the ground and water surface air temperatures. When the westerly contrast shift is prolonged but not great, this means that the ocean is supercooled while the continent is warm and the air moves over the homogeneous underlying surface without experiencing the effect of thermal heterogeneity of the sea and dry land.

Central Asia can serve as another example. The winter synoptic processes of this territory are characterized by predominance on the southwestern periphery of the Siberian anticyclone, which can be either cold or warm. Depending upon this factor, the winter in Central Asia is severe, with a prolonged ice cover on the greater extent of the Amudar'ya and Syrdar'ya Rivers with floating ice on rivers in the extreme south, or is so warm that the ice cover only exists in the low water stretches of the Syrdar'ya River. Inasmuch as the Siberian anticyclone begins to form as early as September, then by November the distribution of air temperature in its vicinity reflects the consequences of the predominant synoptic situation, namely the temperature of the invading air masses and their transformation.

This process is relatively stable and the anomaly of atmospheric temperature in the western part of the Siberian anticyclone in November serves as a

quantitative criterion when forecasting the duration of the ice cover.

Another regional feature of the synoptic processes is used to forecast the spring ice phenomena. The cold flowing into Central Asia in winter usually stands there, causing later thawing, and the anomaly of air temperature in January, now already over regions of Central Asia, correlates well with the dates of thawing of the low water stretches of the Amudr'ya and Syrdar'ya Rivers (1).

Investigators involved in statistical methods of weather forecasting are relying more and more on parameters which characterize the synoptic conditions over extensive expanses, rather than upon data relating to individual meteorological stations. The methods of obtaining such parameters are extremely varied.

One of the methods is expansion of the meteorological fields according to the Chebyshev orthogonal polynomials. Expansion of the barometric and thermal fields in the form of series relevant to the indicated polynomials is a simple and convenient method of analytically presenting these fields. The parameters of expanding the fields of air pressure and temperature anomalies in March, according to the Chebyshev polynomials, are the basic argument of the method of long-term forecasts of thawing of the Lena, Ob', and Irtysh Rivers.

In order to obtain the forecasted date of thawing of the Ob' River near the city of Surgut, the equation has the following form:

$$\Delta D = 0.81 - 1.6A_{00} - 6.7A_{01} + 20.4A_{22},$$

where ΔD is the deviation of the date of freezing from the norm; A_{00}, A_{01}, A_{22} - the parameters of expanding the temperature anomaly fields.

A similar kind of forecast equations were also obtained for other points on the examined rivers. The timeliness of the forecast thereby obtained fluctuates from 22 to 44 days.

The accuracy of the relationships is estimated by the relation $\frac{s}{\sigma}$, where s is the mean square error of the verification forecasts; σ is the mean square deviation of the predicted date of ice appearance (debacle); $\frac{s}{\sigma}$ fluctuates from 0.48 to 0.79 with a permissible value taken according to the "regulations governing the forecasting service", which is 0.80 when the number of members in a series $n \geq 25$.

This method of expansion is the simplest one and does not require high technical expenditures. But at the same time, it is somewhat formal, since in this instance the examined field is broken down into a number of components (elementary fields) which represent certain geometrical stereotypes which cannot always be provided a physical interpretation. In order to avoid this, one can represent the field of pressure and temperature with the aid of so-called natural components (the natural orthogonal functions). The elementary fields obtained in this case are not formal geometrical standards, but reflect the actual atmospheric processes and make it possible to concentrate a high volume of information about the given field in a comparatively small number of parameters of field expansion.

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Despite the fact that the method of expanding the meteorological elements according to natural orthogonal functions has a veritable number of valuable properties which have been examined in the literature in sufficient detail (2, 4), still it is very complex for purposes of computation since it requires computer calculation, and of course, is not the only method of obtaining meteorological information. The use of this method in the Laboratory of Ice Forecasts of the Hydrometeorological Center of the USSR began in 1968 to develop long-term forecasts of the appearance of floating ice on rivers (5, 6, 8). The concept of natural components for use in long-term forecasts of ice phenomena on rivers requires additional research. With this goal, it is necessary to analyze atmospheric processes of the Northern Hemisphere, and to choose regions above which the processes determine the development of ice phenomena on the studied rivers; it is only in this case that the natural components can correctly reflect characteristics of the synoptic processes.

Afterward, the pressure and temperature fields as well as the H_{500} field were expanded according to the natural component. The effect of expanding the field into components consists in that the information about the field component of a field formed by many points is concentrated in a few components which adequately fully impart the basic properties of the initial field. During expansion, a process of successive separation of the field into totalities of fields occurs; evidently, those types of circulation which are most frequently encountered and yield an estimate of the weights of these fields of the examined set.

The latter circumstance, i.e., the possibility of presenting the initial field in the form of a set of a limited number of fields having a certain type of circulation, led to the idea of comparing them with sets of fields obtained when the field of times of ice appearance on the rivers was expanded. Fields of anomalies of air temperature for October were compared with fields of deviations of the dates of ice appearance after 1 October on the Severnaya Dvina, Pechora, the upper course of the Kama, the Irtysh, the Ob', Yenisey, Lena and Amur Rivers.

Table 1 gives the results of this comparison according to the amount of information on the initial field contained in 1, 2, or more (up to 10) expansion fields. It follows from the tabular data that already the first 6 components contain 91% of information about the initial air temperature anomaly field in October and 95% of the date fields of ice appearance.

Table 1
Summary Information (%) About the Air Temperature Anomaly for October and the Times of Appearance of Ice, Contained Successively in the First Ten Expansion Fields

Number of expansion fields	1	2	3	4	5	6	7	8	9	10
Air temperature anomaly	43	63	75	83	89	91	93	95	96	96
Times of ice appearance	80	85	88	92	94	95	96	97	98	98

Maps of the eigenvectors of the temperature anomaly field expansion for October and the dates of ice appearance were drawn. The direction of the isolines which outline the uniform values of natural components are similar.

The first eigenvector (X_1) of the ice appearance dates contains 80% of the information. The region of negative values encompasses the Yenisey River, the lower course of the Ob' River, the upper course of the Amur River and the Pechora River. The zero line runs through the city of Troitsko-Pechorskoye (the Pechora River), Oktyabr'skoye tributary (the Ob' River), the city of Krasnoyarsk (the Yenisey River), and through the upper course of the Shilki and Arguni Rivers. It crosses the Amur River at the city of Vlagoveshchensk. Such a layout of the zero line corresponds to a 90% frequency curve of the dates of ice appearance on 31 October, cited in a work (3).

The layout of the foci of positive and negative values (the points) on the map of eigenvector X_1 signifies that when the ice appears early on the Lena and Yenisey Rivers, as well as on the lower courses of the Ob' and Pechora Rivers, it is more probable to anticipate the appearance of ice later than normal on the middle course of the Ob' River, on the Irtysh River, on the upper course of the Kama River, and on the Severnaya Dvina Rivers.

In order to obtain a quantitative characteristic of the relationship between eigenvectors, coefficients of expansion for a 30-year series of temperature anomaly fields and dates of ice appearance were correlated. Table 2 gives the values of the obtained correlation coefficients. It is characteristic that the highest values of the correlation coefficients were obtained with uniform expansion coefficients (with the exception of B_5 and B_7).

The zero line outlines a region of disposition of the Siberian anticyclone on the maps of anomaly of the x_2 temperature field. In these cases, the ice appears on the upper courses of the rivers earlier, which is due to the cold anticyclone weather associated with the Siberian anticyclone.

Field x_3 of the ice appearance dates is characterized by its meridional nature. The appearance on rivers of this type can be due to two characteristic processes: the invasion of anticyclones from the Barents Sea into the Ob' River basin, and the invasion of anticyclones from the Karsk Sea to the middle course of the Lena River.

These three fields not only determine the time of appearance of the ice on the rivers, but also determine to a certain extent their distribution for different rivers in time. Hence, in the future during the forecasting of ice appearance times, the established affinity in the distribution of natural components of the eigenvectors of pressure and temperature anomaly fields for the month preceding the appearance of the ice and the fields of ice appearance dates can also predict the course of the process of river thawing in time, with a certain degree of probability.

During the development of methods of long-term forecasts of the ice appearance times on rivers of the northern ETS (the Severnaya Dvina and the Pechora), of Siberia (the Ob', the Irtysh, the Yenisey, the Angara and the Lena), and of the Far East (the Amur), it was established that obtaining the forecast indicators for October, i.e., for the month in which, as a rule, ice formation begins on the listed rivers, it is best to use the characteristic of atmospheric circulation for July and August.

Table 2

Value of Correlation Coefficients Between the Expansion Coefficients Relevant to the Natural Components of the Air Temperature Anomaly in October ($B_1 - B_{10}$) and the Dates of Ice Appearance (in deviations from $1/X$) ($B_1 - 10$)

Expansion Coefficient	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	B_{10}
B_1	−0.39	−0.36	−0.13	−0.02	0.09	0.37	0.08	0.23	−0.05	−0.30
B_2	−0.17	−0.57	−0.03	0.18	−0.30	−0.21	−0.17	−0.20	−0.02	0.05
B_3	−0.37	−0.28	0.61	0.21	0.18	−0.19	0.13	0.04	0.11	−0.06
B_4	0.02	−0.19	−0.31	−0.22	−0.01	−0.03	−0.30	0.34	−0.05	0.18
B_5	0.01	0.36	0.18	−0.19	−0.18	0.03	−0.07	0.10	0.02	−0.23
B_6	−0.07	0.06	0.02	0.01	0.08	−0.48	0.01	0.04	−0.07	−0.19
B_7	−0.20	−0.26	0.29	0.20	−0.14	0.10	−0.30	−0.01	0.12	−0.13
B_8	−0.31	−0.05	0.01	0.04	−0.09	−0.25	0.01	0.49	−0.23	−0.21
B_9	−0.22	−0.16	−0.36	0.20	0.06	−0.08	−0.26	−0.16	−0.50	−0.11
B_{10}	−0.07	0.16	0.04	−0.14	−0.05	−0.09	−0.37	−0.05	0.24	−0.37

(Note: commas should be read as decimals.)

Coefficients of expansion of the pressure and temperature anomaly fields were used as this characteristic, according to the natural component in a certain region of the Northern Hemisphere. This is significant for the given river basin. The coefficients of expansion of the meteorological element fields for September for certain rivers, as, for example, the Amur, is intimately related with the times of appearance of the ice, which makes it possible to use it to refine the long-term forecast.

The intimate relationship of the atmospheric processes of July, as well as those of August and September, with the appearance of the ice on rivers, which occurs in October, is not random, but is confirmed by the investigations conducted by a number of authors who identified an association between the temperatures of the air in July (August and September) and October (7).

The long-term forecast of the times of ice appearance on the Severnaya Dvina, Pechora, Ob', Irtysh, Yenisey, Angara, Lena and Amur rivers involved taking the parameters of expansion as the basic arguments according to the natural components of the pressure and temperature anomaly fields for July - September in different sectors of the Northern Hemisphere. The characteristic sectors were chosen as the result of a careful analysis of atmospheric processes in these months of the year, when the appearance of ice was observed at times which significantly deviated from the average multiannual times.

In order to obtain the forecasting relationships for the Amur, Yenisey and Angara rivers, it was necessary to use the parameters of expansion of the pressure and temperature anomaly fields of the air over eastern Siberia and the Pacific Ocean as arguments; for the Pechora River, the lower course of the Ob' and Lena rivers - those over Canada, while for the middle and upper courses of the Lena River, those over western and eastern Siberia had to be used. For the Severnaya Dvina, the Ob' (excluding the lower course) and the Irtysh rivers, it is necessary to have the parameters of expansion of the pressure and temperature anomalies over the Atlantic Ocean, Europe, and western Siberia.

As an example, we cite the equation which can be used to compile the forecast of ice appearance dates according to the July data for the Severnaya Dvina River near the city of Kotlas:

$$\Delta D = -3.5 + 1.3B_1 + 1.7B_2 - 1.1B_3 + 1.4B_4 - 0.2B_5 - 1.3 B_6,$$

where ΔD is the deviation of ice appearance times from the normal date near the city of Kotlas; $B_1 - B_4$ are the expansion coefficients of temperature anomaly fields in July over ETS and western Siberia; $B_5 - B_6$ are the field expansion coefficients of the pressure anomaly in the same location.

The number of field expansion coefficients over each region was selected on the basis of estimating the contribution of the individual components to total dispersion. As has been shown in many studies, the primary contribution falls to the first ten members of the expansion, which reflect the most significant field characteristics; of these, no more than 7 usually enter the forecasting equations. This is because when the number of variables increases, the requirements made upon the volume of initial data rapidly grow and the

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calculation errors increase. And we have at our disposal only the observations of the ice phenomena over 30 - 60 years.

The timeliness of the obtained forecasts for the rivers listed above is only about 2 months (the forecast is compiled at the beginning of August). The estimate of the forecast relationships satisfies the requirements of the "regulations pertaining to the forecasting service".

The results of the work and the estimate of the obtained recommendations demonstrate the promise of employing synoptic-statistical analysis of meteorological fields for ice forecasts. In future, it will be expedient to test the applicability of this principle to other regions, as well as for other types of hydrological forecasts.

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MODERN PRINCIPLES OF DEVELOPING METHODS OF SHORT-TERM FORECASTS OF ICE PHENOMENA ON RIVERS AND RESERVOIRS

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So-called physico-statistical relationships began to replace purely empirical ones over two decades ago in short-term forecasts of ice phenomena. The physico-statistical relationships differ from the empirical ones in that they reveal the direct relationship of the ice phenomenon with the "physically" based factors which determine it; and only certain coefficients are established empirically, on the basis of many multiyear series of observations. With each passing year, the physico-statistical methods of forecasts develop and improve. In many cases they are converted into calculations, i.e., those for which multiyear series of observations are no longer required. An example can be the method of forecasting Autumn ice phenomena developed by L. G. Shulyakovskiy and universally adopted into practice.

The method of developing the forecast relationships itself has been improved. A method of dimensions and a theory of similitude, and a method of mathematical and physical modeling of the processes are extensively used.

New types of short-term forecasts have appeared: predictions of the ice edge in the lower water areas of hydroelectric stations, the debacle and clearing of reservoirs, the stability of the melting ice cover, etc.

Certain new methods of forecasting are briefly described below.

1. Based on the general conditions of the onset of ice formation on the water surface developed by Shulyakovskiy (10) and expressed by the inequality

$$\vartheta_t \leqslant -\frac{B_t}{\alpha_t}. \tag{1}$$

(ϑ_t - average cross-sectional water temperature; B_t - specific heat exchange of water surface; α_t - coefficient of heat transfer from the water to the surface), as the result of refining certain parameters, an equation has been obtained for calculating water temperature not only for the period of onset of the Autumn icing phenomena, but also for any other time of the year (11).

On the basis of the same general conditions of the onset of ice formation, an equation has been derived for calculating the position of the stretch of ice formation on stretches of rivers below a hydroelectric power plant:

$$l_0 = -\frac{hvc\rho}{k} \ln \frac{-\frac{B_t}{\alpha_t} - \bar{\theta} - \frac{d+q}{k}}{\vartheta_0 - \bar{\theta} - \frac{d+q}{k}}, \tag{2}$$

here l_0 is the distance from the initial stretch (from the hydroelectric power plant dam or from the stretch for which one has water temperature data) to the

stretch where ice formation begins; h and v - respectively, the average depth and average flow rate on the heat exchange stretch (i.e., on a length l_0); k and d - parameters which characterize heat exchange with the atmosphere; l_0 - water temperature at the beginning of the stretch; Θ - temperature of the air averaged over the stretch; q - influx of heat from the ground and subterranean water over the stretch.

Since most of the initial values are taken as averages over a stretch whose length l_0 is the sought value, then the calculation is made by the method of successive approximation (3).

2. Improvements have been made in the method of forecasting the dates of ice cover (the dates of formation of ice necks on rivers). The relationships between the critical temperature of ice cover formation Θ_{cr}, on the one hand, and the totals of negative air temperatures at the point of formation of the neck ($\Sigma\Theta_M$) and on the path of movement of the ice ($\Sigma\Theta_M$), as well as the hydraulic-morphometric parameters, on the other hand, have been determined by the dimensionalities' method. When obtaining the calculation equations, the materials of aviation surveys and special observations carried out by the Gidroenergo-proyekt were used. The result was obtaining the following two equations:

$$\Theta_{cr} = -\frac{3.56 v^{1.93} b^{0.80}}{(\Sigma\Theta_M)^{0.46}(\Sigma q)^{0.30}} \tag{3}$$

and

$$\Theta_{cr} = -6.5 v^2 \left(\frac{b}{\Sigma\Theta_M}\right)^{0.8}. \tag{4}$$

A check showed that the accuracy of the calculation made according to the equations (3) and (4) is significantly higher than that yielded by the previous Shulyakovskiy equations (10). The comparison also showed that the equation (4), despite the fact that it is only slightly simpler, has poorer accuracy than equation (3). Equations (3) and (4) are identically applicable for calculating the beginning of the ice cover formation on rivers with natural and regulated water regimes.

3. Great changes have occurred in the field of short-term forecasts of the Spring ice phenomena. A model of the debacle process has been developed which takes into account the primary property of the melting ice - the reduction in its strength.

The ice cover on the reservoir is viewed as an infinite or semi-infinite plate lying on an elastic base and subject to a vertical wind load (1). The condition of its destruction is the following

$$\varphi h^{1/2} \leqslant a w^2; \tag{5}$$

here ϕ is the relative destructive stress of bending, equal to σ/σ_0; σ - destructive stress of the melting ice; σ_0 - destructive stress for ice not exposed to the effect of sunlight and having zero temperature; h - thickness of the

melting ice; w - wind velocity (greatest for the given day of the four times of observation); a - an empirical coefficient which must be determined for each reservoir from the multiannual series of observations. As experience shows, coefficient a is constant and equal to 0.018 for many reservoirs. In this case the ice thickness should be expressed in cm and wind velocity should be expressed in meters per second.

Condition (5) determines the moment (date) of the beginning of the ice drift. It proved that the date of reservoir ice clearance is forecasted well according to the date of the onset of drift and the amount of heat necessary (according to calculation) to melt the remaining ice. The clearance date can be forecasted with a timeliness ranging from 5 to 12 days and is not required during the compilation of meteorological data.

The ice cover on rivers was viewed as a strip loaded by a compressing, elongating or bending force created by the flow (12). With any of the loads (or during their simultaneous effect), the condition of debacle can be expressed in the following way:

$$\varphi h \leqslant f(H, \, \Delta H),$$

$$(6)$$

where H is the water level during debacle; ΔH is the rise in level by the moment of debacle over the maximum Winter level or over the level at the onset of the Spring rise. Relationship (6) is established individually for each river (river stretch) according to the multiannual observation series.

When condition (6) is used to forecast the debacle, it is more convenient to determine the derivative φh not dependent upon level, but upon the flow rate of water. In this case the debacle condition acquires the following appearance:

$$\varphi h \leqslant \bar{f}\left(Q^2, \, \frac{b_\pi}{b_p}\right);$$

$$(7)$$

here, Q is the predicted flow rate of water on the day of debacle; b_i and b_r - respectively, the width of the ice cover and the width of the river of the day of debacle and b_i is associated with the level above which the stretch is satisfied while b_r is associated with flow rate on the day of debacle.

The structure of equation (7) is found on the basis of a series of multi-annual observations. Thus, for the Oka River near the city of Kashira, expression (7) acquires the following form:

$$\varphi h \leqslant 2 + 50\left(1 - \frac{b_i}{b_r}\right)Q^2 \cdot 10^{-6}.$$

$$(8)$$

There is basis to assume that the numerical values in expression (8) depend upon the hydraulic-morphometric parameters of the specific stretch of river. This permits one to hope in future to find a universal expression for the debacle conditions of any river without using multiannual observation series.

4. The continuously changing strength of the ice is taken into account in the

model of the process of destruction of the melting ice which is the basis of the methods of calculating and forecasting the dates of debacle of rivers and reservoirs.

It has been established that the strength of the melting ice decreases under the effect of solar radiation, namely:

$$\varphi = \left(1 - \sqrt{\frac{S}{S_0}}\right)^2,$$

(9)

where S is the amount of heat of solar radiation absorbed by the ice (cal/cm^3); S_0 is the amount of heat of solar radiation at which the ice totally loses strength. On the average for rivers and reservoirs, S_0 = 47 cal/cm^3, but it can fluctuate within broad limits (1) depending upon the structure of the ice.

The amount of heat S over the course of the melting period continuously accumulates and depends upon the amount of solar radiation that strikes the ice, the thickness of the ice in which the absorption of solar radiation occurs, as well as the thermal balance in the upper surface of the ice cover. When there is a negative thermal balance, the heat S accumulated by the ice in the form of melt water in the ice layer partially and occasionally fully is expended (i.e., the melt water again freezes).

The value of φ is calculated in parallel with the calculation of ice thickness. A precise determination of φ and h for the given days requires a layer-by-layer calculation taking into account the distribution of absorbed solar radiation through the thickness of the ice. This method is laborious without using a computer, but is preferable if one has a computer, particularly when establishing the forecasting relationships.

A less laborious method that does not require a computer but is also less accurate can also be successfully used, particularly for compiling the operating forecasts (2).

The method of calculating the strength of the melting ice cover made it possible to issue a new type of forecast, namely a forecast of the thickness and strength of the ice cover on reservoirs. This forecast is used to determine the optimum time of beginning the operation of lake icebreakers.

5. The transition from the empirical methods of forecasting to the physico-statistical ones required refining the physical and mechanical properties of the ice and snow as well as the development of a method of determining a number of new ice characteristics. For example, the albedo of melting ice was refined (4, 5), and a relationship of the ice albedo with meteorological conditions was established. The concept of the capacity of the ice to absorb solar radiation (1, 7), etc. was expanded.

Determining the influx of the heat of solar radiation to the ice cover required reliable information about the albedo of the ice and its absorbing capacity. It became clear that the albedo of the ice is a variable value as the result of analyzing and generalizing available observation materials. Albedo depends upon the condition of the ice surface and upon meteorological conditions. A relationship of albedo with the course of air temperature, the

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type of precipitation and overcast was established for the Lena River. This makes it possible quite accurately to calculate albedo for each day of melting (5). At precisely the same time, the average value of the ice albedo is quite constant over the entire melting period (0.30 - 0.35).

Analysis of the observation materials of different authors relating to the absorption of solar radiation by the ice showed that ice absorbs the Sun's rays selectively and the spectrum of radiation striking the ice surface is extremely heterogeneous and depends upon the atmospheric humidity, overcast and height of the Sun. Therefore, the absorption of solar radiation by the ice is not subordinate to the Buger-Lambert law, but is approximately described by the following empirical formula

$$\frac{I}{I_0} = e^{-ch_i^{0.6}} \tag{10}$$

where I_0 is the radiation entering the ice; I is the radiation passing through ice having a thickness of h_i; c is the absorption factor, which depends upon the structure of the ice.

The precise determination of the absorption factor for the ice cover of different water objects and establishing the principles of the change in any absorption factor in different physico-geographic regions is a problem for years in the immediate future.

The calculation of the thermal balance on the surface of the water in Autumn or on a surface of the melting ice in Spring requires precise values of the meteorological elements over these surfaces. The temperature difference, atmospheric humidity and wind velocity over the water and ice surfaces and over dry land is sometimes so great that it can totally distort the results of calculating ice melting if the data of a shore meteorological station are used without making the reducing corrections in them. The difference in the value of meteorological elements is especially high in Spring, after the snow has melted away from the soil. At this time the air temperature over dry land can be 5 - 7° higher than over the ice cover.

The observations showed that the difference in temperature and humidity of the air over dry land and the ice cover depends not only on the absolute value of these elements, but also on the degree of overcast and wind (5). As a rule, the larger the water object, the greater the change in meteorological elements above it. However, these differences can be significant even above a comparatively small river as a consequence of the deep cut of the channel or the level of protection of the shore meteorological observation station. Hence, in order to obtain reliable data about the thermal balance, one should establish the transition coefficient from the shore meteorological station to the examined object. This is a problem for the immediate future.

6. The transition to the physico-statistical and calculation methods of forecasting ice phenomena does not signify abandoning the more simple forecast relationships, if they do not contradict the physical concept about the process and provide accurate results. For example, it is known that the calculation method of forecasting the Autumn ice phenomena does not rule-out the use of physico-

statistical relationships structured on the basis of a multiannual series of observations. Furthermore, the simple relationships occasionally provide more accurate results than the calculation methods. For example, forecasting the dates of the ice cover according to the total of negative average daily air temperatures and the critical temperature determined on the basis of water level can be more accurate than that done according to the calculation method because it is difficult to determine the necessary hydraulic-morphological characteristics for the calculation.

The calculation of ice strength (value ϕ) is quite laborious and requires information about meteorological elements. At precisely the same time, when one is compiling the debacle forecast (according to the prepared method), particular accuracy in determining ice strength is unnecessary. Therefore, the possibility of determining the relative strength of the ice cover ϕ according to the number of days n from the onset of melting (from the date of the snow's departing the ice) and the initial ice thickness h_0 was investigated. The following expression was obtained for the Ussuri River (8):

$$\varphi = \left(1 - \sqrt{\frac{n}{0.36 h_0}}\right)^2.$$

(11)

Equation (11) is also suitable for other rivers, specifically for regions where the Spring is usually sunny (Siberia, the Far East).

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CALCULATING THICKNESS OF THE ICE COVER ON RIVERS AND RESERVOIRS FOR ICE PHENOMENA FORECASTING PURPOSES

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The accuracy of forecasting the thickness of the ice cover on rivers and reservoirs, as well as the time of debacle and their clearance from ice depend to a significant degree on the correct estimate (diagnosis) of the current ice thickness. Today, the diagnosis of ice cover thickness is generally based on standard observations of the water-metering station. As is known, in a number of cases these observations poorly characterize the thickness of the ice on the water object in general. The materials obtained from ice measuring surveys carried out on rivers in the European Territory of the USSR show that the thickness of the ice at the stations in the initial period of icing is usually less than the average thickness of the ice on river stretches near the stations, while in Spring, on the contrary, it is greater. Differences in individual years have reached 10 - 12 cm and more. The causes of this are obvious. In the Autumn, the ice forms near the shore (ashore) earlier; at the end of Winter and in the period of the Spring thaw the ice cover is thinner in the shore zone than in the middle of the river due to the influx of warm ground and melt waters from the shore.

For the Oka River (10), the correlation coefficients of the relationship of ice thickness at the stations from the middle in the stretch of river or on a stretch of river near the station fluctuate from 0.84 to 0.91. Deviations within limits of ±2 cm had a guarantee factor of 29 - 44% and within limits of ±10 cm - 82 - 91%. The greatest deviation reached 20 cm in the presence of polynias (stretches of clear water in ice) and the Autumn ice accumulations.

Measurements made on a characteristic stretch of water and shallows of the Oka River near Novinka station confirmed the established opinion regarding the thinner ice in shallows. This is explained not only by an elevated influx of heat to the ice from water in the shallows, but also by the later establishment of the ice cover and the excessive accumulation of snow in individual years on the rough surface of the ice cover.

The height of the snow on the ice measured at stations on the Oka River was most often lower than its average height on the hydrometric stretch of water (correlation coefficients of about 0.30). This indicates the necessity of changes in the set-up of observations made of snow at the stations.

The people who devised the method of calculating the thickness of the ice which is presented below have as their goal not only to enhance the accuracy of diagnosing the current thickness of the ice, but also determining it for a multiannual series of past winters. These data are necessary during the development of a method of long-term forecasting of the dates by which the ice achieves a certain thickness, the debacle times and the times at which water objects are clear of ice, as well as for other purposes.

The basis of the method of calculating the build-up in thickness of the ice cover from the lower surface is a variation of the known Stephan formula. The formula characterizes the steady process of build-up in the absence of a ready ice material and an influx of heat from the water to the ice:

$$\Delta H_I = - \frac{\lambda_{I} t_{I,s}}{L \rho_I \left(H_I^0 + \frac{\lambda_I}{\lambda_s} h_s \right)} \Delta \tau, \tag{1}$$

where $t_{i,s}$ - temperature of the surface of the ice or snow on the ice; L - heat liberated during the crystallization of water (80 cal/g); $\Delta \tau$ - time; ρ_i - density of the ice cover (assumed to be 0.91 g/cm^3); H_i^0 and h_s - thickness of the ice cover and height of snow on the ice (cm); λ_i and λ_s - respectively, heat conductivity of the ice cover (assumed to be 0.0052 cal/(cm · degree ·sec) and snow on the ice.

In order to determine the maximum pre-Spring ice thickness on rivers (2) and reservoirs (4), the entire period of ice build-up is divided into cycles ($\Delta \tau$) of varying duration. The boundaries of the cycles are days with snowfalls, snow drifts and thaws which alter the thermal equivalent of the snow-ice cover by several tens of centimeters. When the ice is thin and has no snow on it, the duration of the cycles should be reduced to a day. When one has persistent anticyclone weather and a significant layer of snow on the ice, one can assume that $\Delta \tau = 10$ days or more.

After substituting the values of heat conductivity, density, and other constants of the ice, formula (1) acquires the following form for calculating ice build-up

$$\Delta H_I = - \frac{6.2 N \sum t_a}{\left(H_I^0 + \frac{\lambda_I}{\lambda_s} h_s \right)}, \tag{2}$$

where $\sum t_a$ - the sum of mean daily air temperatures for the meteorological station; N - transition coefficient from air temperature at the meteorological station to temperature of the surface of the ice and snow on the ice; $H_I^0 + \frac{\lambda_I}{\lambda_s} h_s$ - average thermal equivalent of the snow and ice cover for the

cycle; H_I^0 - thickness of the ice cover at the beginning of the cycle. The thickness of the ice at the end of the given cycle is in fact the initial thickness for the next cycle and is assumed to be $H_I^0 + \Delta H_I$.

A comparison of the meteorological data over the ice of a number of water objects and over dry land has shown that the meteorological stations on dry land at which wind velocity is similar to their values over the water object are more representative; the distance to the meteorological station has less significance. Therefore, the meteorological stations exposed to the wind are

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representative of broad reservoirs.

Coefficient N is found according to two relationships (4), which take into account the relationship between air temperature at a height of 2 m over the ice and the temperature of the surface of the ice or the snow cover on the ice. Heat conductivity of the snow is determined according to its relationship with density (4).

The effect of winter thaws on the height of the snow cover is determined according to the empirically found relationship of the decrease in height with the total of daily positive air temperatures. The density of the snow soaked by melt water, was taken according to the data of P. P. Kuz'min (1947).

A more precise calculation of the build-up in thickness of the ice cover is necessary for the initial period of icing. The calculation is made for six-hour time intervals ($\Delta \tau = 0.25$ days) according to the following formula:

$$\Delta H_{I} = -\left[\frac{6.2t_{I,s}}{\left(H_{I}^{0} + \frac{\lambda_{s}}{\lambda_{s}}h_{s}\right)} - \frac{\Delta P}{L_{\rho}} \right] \cdot 0.25, \tag{3}$$

where ΔP is the influx of heat to the ice from the water, in cal/(cm^2 days); the other symbols are as before.

The temperature of the surface of the ice or the snow on the ice $t_{I,s}$ is calculated by the method of thermal balance according to the meteorological elements. For this purpose, effective radiation was calculated after A. P. Braslavskiy and Z. A. Vikulina (1954), heat exchange resulting from the evaporation (condensation) of snow (ice) and convection heat exchange with the air were taken according to B. D. Zaykov (1955). The influx of total solar radiation under conditions of cloudless weather was determined according to V. N. Ukraintsev (10). Corrections for overcast, albedo, and the absorption of radiation by the ice were made according to the authors' recommendations (5).

The sought temperature of the ice or snow surface enters the thermal balance equation in a power no less than the square, and this complicates its determination. Therefore, the entire range of temperatures of the ice (snow) surface which is usually found at the ETS was divided into five components, for each of which the surface temperature could be expressed by a first degree equation after certain simplifications.

After substituting the values of $t_{I,s}$ in formula (3), five equations were obtained for calculating the ice build-up (in cm) over a six-hour period:

$$\Delta H_{I} = 1.55 \frac{[(m + 0.003w)\,t_{a} - z_{i} - (0.007 + 0.0051\omega)(R - e) + z_{0}]}{\left[\left(H_{I}^{0} + \frac{\lambda_{I}}{\lambda_{s}}h_{s}\right)(P + qw) + 0.312\right]} - \frac{\Delta P}{288}; \tag{4}$$

here, ω is the wind velocity at a height of 2 m over the surface of the ice cover (m/sec); t_a, e - temperature ($^{\circ}$C) and absolute humidity (mb) of the air at a height of 2 m over the ice; $\lambda = 0.312$ cal/(cm X degree · min).

The accepted values of the coefficients m, R, P, and q in equation (4) are given in the table depending on air temperature.

Coefficient	0.0−4.5	−4.6 −10.5	−10.6 −17.0	−17.1 −29.0	−29.1 −40.0
m	0.0110	0.0101	0.0098	0.0093	0.0085
R	6.1	5.6	4.4	2.7	1.3
P	0.0140	0.0121	0.0111	0.0099	0.0082
q	0.0052	0.0045	0.0039	0.0034	0.0032

The calculation made according to the equation (4) is quite laborious, and therefore special tables were compiled (9), with whose aid the build-up of crystalline ice on the lower surface of the ice cover over six-hour time intervals was found according to the separately calculated thermal equivalent, the known daily temperatures of the air, overcast and wind velocity.

The ice thickness was determined according to the "step-by-step" system by totalling the initial thickness of the ice H_1^0 at the moment of the ice development with the increment over a cycle ($\Delta\tau$), in this case over each six-hour period.

With the calculations carried out according to the equations (4), as when compiling the tables, a refined relationship of heat conductivity of the snow with density (cal/(cm · degree · sec)) was used

$$\lambda_s = 0.0068\rho_s^2 + 0.00009. \tag{5}$$

The most important factor which determines the intensity of build-up of the ice cover is the snow cover, whose heat insulating properties depend on its depth (height) and density. These characteristics were calculated according to the data of the meteorological stations and the precipitation measuring stations.

The mean height of the layer of freshly fallen snow on the ice cover with the absence of evaporation and drifting depends on the amount of incoming snow and its density; its amount for narrow water objects was taken according to the data of the precipitation gauge mounted in locations protected against the wind (under the protection of trees in the fields, in orchards, etc.). For large lakes (Il'men' and others), and reservoirs, it is evidently more expedient to use data on the precipitation measured at meteorological stations open to the wind. There under sampling of solid precipitation because of the effect of the wind reflects the losses of snow to evaporation and its drifting from the ice under conditions of strong wind transport to a known degree.

The density of the freshly fallen snow is found in relation to wind velocity with the onset time of snowfall to the time of its measurement.

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When wind velocity is less than 4 m per second (at the height of the wind sock), the surface of the ice or old snow will be entirely covered by fresh snow (there is no snow drifting). Deviations in the form of separate accumulations are observed during snow drifting (a wind whose velocity is in excess of 4 m per second). The degree of surface coverage depends on the amount of incoming snow and wind velocity, which characterize the intensity of drifting (5). On large reservoirs incomplete coverage of the ice by snow (a mottled landscape) is noted in the course of almost the entire first half of the Winter. In this instance large fluctuations in the thickness of the ice over the reservoir's aquatorium appear.

Under mottled landscape conditions, the mean build-up in the thickness of the ice ΔH_I is determined according to the following formula

$$\Delta H_I = \Delta H_I^0 (1 - S) + \Delta H_s^0 S. \tag{6}$$

where S is the proportion of surface of the water object covered by snow; ΔH_I^0 and ΔH_s^0 are, respectively, the build-up of ice on sectors without a snow cover and under snow.

On the basis of using the indicated relationships, as well as formulas (5) and (6) and certain assumptions, a number of relationships of the type (6) was suggested (5) to calculate the build-up of ice over the course of the entire period of the mottled landscape. With a continuous cover of the ice by snow, the intensity of build-up over the aquatorium levels-off and its mean thickness can be calculated according to the average thermal equivalent of the snow-ice cover.

Thaws significantly reduce the depth of the snow cover on the ice and increase its density. The decrease in the depth of snow due to settling during a thaw Δh_s with a density of 0.17 - 0.30 g/cm^3 comprises approximately 25% of the calculated thawing layer and also depends on the depth of the snow layer:

$$\Delta h_s = 1.25 \frac{Q}{80\rho_0} - 0.042 (19 - h_0); \tag{7}$$

here Q is the influx of heat to the surface of the snow during thawing, determined according to the formulas cited earlier for calculating separate components of the thermal balance; ρ_0 and h_0 are the initial (before the warming period) density and depth of the snow layer, respectively.

The density of the snow during the thaw increases because of its settling and saturation with water. Before termination of the water retaining capacity of the snow, the density of the snow can be determined on the basis of the mass conservation condition $\rho_0 h_0 = \rho_k h_k$, where ρ_0 and h_0 are the density and depth of the snow before the thaw, ρ_k and h_k are the same characteristics after the thaw. Thence, according to formula (7), we obtain

$$\rho_k = \frac{\rho_0 h_0}{\left\{ h_0 - \left[1.25 \frac{Q}{80\rho_0} - 0.042 (19 - h_0) \right] \right\}}. \tag{8}$$

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The water retaining capacity of the snow changes significantly and, according to V. D. Komarov (1957) it comprises less than 10% on a "strongly recrystallized" snow (firn), and up to 30% on a "finely granular" snow. This is approximately 2 times less than the figures provided by P. P. Kuz'min (1947). It should be pointed out that there are no reliable methods of calculating the water retaining capacity of the snow, inasmuch as the water retaining capacity depends strongly on the structure of the snow cover and not on density alone.

The excess melt and rain water q_m accumulates on the surface of the ice cover and saturates the snow. After the snow and water mixture freezes, a snow-ice of the following thickness forms (in cm)

$$h_{s.I} \simeq 1.06 \frac{q_m}{\left[1 - \left(\frac{\rho_s}{0.92} + u\right)\right]},$$ (9)

where ρ_s is the amount of solid phase in the snow and water mixture (g/cm^3);

u is the amount of air expressed in proportions of a unit of volume of the mixture (usually 0.02 - 0.05).

The ice material (brash ice, etc.) which lies beneath the ice cover in the amount K (g/cm^3) hastens its build-up according to the following equation

$$\Delta H_b = \Delta H_I \sqrt{\frac{1}{1-K}},$$ (10)

where ΔH_I is the calculated magnitude of ice build-up.

Measurements of the density of brash ice and accumulations of other ice material (sludge, slush, etc.), made after the establishment of icing, make it possible to take into account its effect on the subsequent build-up in the depth of the ice cover. In the absence of such measurements the effect of the ice material on the build-up in ice thickness can be taken into account according to the following empirical relationship (2)

$$H_{I.obs} = \Delta H_{I.cal} \left[1.23 + (0.62 - 0.0053T)\left(\frac{\Delta R}{100}\right)^2 - 0.0014T\right],$$ (11)

where ΔR is the difference between the water level from the first day of appearance of ice phenomena and the lowest pre-icing (serves as an indicator of the consumption of water by ice formation); T - number of days from the day of icing to the date of the ice measurement survey. The correlation coefficient of the actual ice thickness and that calculated according to the equation (11) is 0.93 and mean square deviation is $\sigma = 5.3$ cm.

The snowy ice is widespread on rivers and reservoirs; it forms where the ice cover is overloaded by snow, accompanied by the overflow of water onto the ice (7). The thickness of the layer of snowy ice is calculated on the basis of the condition of hydrostatic equilibrium of the snow-ice cover (3, 7). In a number of cases this equilibrium is not achieved because of a deficiency of openings in the ice cover as well as because of freezing of the overflow water.

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Therefore, the following empirical relationship (1) yields the best results

$$H_{s.I} = 0.62 \, (h_s^{field} -- h_s^{ice});$$

(12)

here, $h_s^{field} - h_s^{ice}$ is the difference in the depth of the snow in a field

(according to the snow survey data) and on the ice (according to a station measurement). The coefficient 0.62 chiefly characterizes the increase in snow density when the snow thaws because of the water which has entered it from below the ice. The relationship (12) has been obtained according to the material of ice measurement surveys. Mean square deviation is 4.7 cm.

Fishermen facilitate the formation of snowy ice. One fishing hole with a significant overload of the ice by snow can cause the formation of snowy ice over an area greater than 1 ha. On small water objects, for example, the Klyaz'minsk reservoir on the Moscow Canal, snowy ice of significant thickness forms almost annually (up to 34 cm in the Winter of 1959 - 1960). On the broad Rybinsk reservoir, relatively less visited by fishermen, the condition of ice overload by snow frequently remains until Spring and the snowy ice is only noted in places.

As observations made at the Klyaz'minsk reservoir (1956 - 1959) and on the Oka River (1970 - 1973) showed, cracks form when a shallow layer of snow exists with significant fluctuations in air temperature. Through cracks only exist when the ice is less than 20 cm thick.

Experience in calculating ice thickness carried out at the Hydrometeorological Center of the USSR for different water objects according to the "step-by-step" cycles have shown that this system enables one to take into account the sharply changing meteorological and hydrological situation. Simultaneously, the need for future investigations was revealed, particularly in the area of the quantitative determination of the influx of heat from ground water.

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PROBABILITY CHARACTERISTICS OF FREEZING AND DEBACLE TIMES OF RIVERS AND
RESERVOIRS OF THE SOVIET UNION

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The freezing and debacle of rivers have a significant effect on the activity
of such branches of the national economy as inland waterway transport and con-
struction, especially the hydrotechnical and transport types, forestry, energy
generation, etc. Specifically, the beginning and end of the navigation period
will still be determined for many years by the times of freezing and debacle of
rivers and reservoirs, despite the technical re-equipment of the inland waterway
fleet.

In recent years, planning practice has adopted economic calculations for
which data on the probability of times of ice phenomena are necessary. The
development of hydrotechnical construction on river mains requires calculating
the probability characteristics of the times of ice phenomena on reservoirs.
The improvement in methods of ice forecasts is also linked with studying the
probability characteristics and space-time relationships of ice phenomena times.

Our investigations on this problem began in 1964, when characteristics of
the probability of times of ice phenomena on navigable rivers of the Soviet Union
were obtained with the aid of plotting empirical curves of the guarantee rating
of dates of the appearance of floating ice, the beginning of icing and the Spring
debacle (and later, the dates of termination of the Spring debacle and magnitudes
of duration of the period of the absence of ice as well, called the period of
physical navigation in inland waterway transport). The published tables of times
having frequency ratings of 2, 10, 25, 50, 75, 90 and 98% in a multiannual series
have been widely used in practice.

The possibility of approximating their guarantee curves was investigated
(4) for purposes of analyzing, summarizing, and calculating the probability
characteristics of the times of ice phenomena. The Pierson III type (binomial)
equation proved to be most suitable for this purpose and has come to be exten-
sively used in hydrological calculations. The use of this equation in the cal-
culations of flow encounters difficulties when extrapolating the values with
very low repetition. In our case such difficulties do not have a significant
effect, since in the economic calculations, unlike the construction ones, such
an extrapolation is usually not required.

A specific characteristic of the calculation of dates is the impossibility
of determining the conventional changeability characteristic - the variation
coefficient C_v. In order to calculate it, one must have some absolute value
which characterizes the norm, i.e., one must establish the beginning of the
time count. Such a beginning will unavoidably be arbitrary, and coefficient C_v
loses the property of an indicator which is comparable for any statistical
series. However, this circumstance does not prevent the use of the binomial
equation. The changeability of dates is characterized by the mean square

deviation of the dates from the norm. According to the parameters calculated from a series of date observations, the average date D, the mean square deviation σ from it and the asymmetry coefficient C_s - it is easy to determine the dates of ice phenomena of any given frequency level p as $D_p = D + σΦ (C_{s,p})$ with the aid of the known Foster-Rybkin tables.

Investigation of the accuracy of determining the parameters of the equations according to the actual series of observations made on rivers showed that the probable errors for the average dates and the mean square deviations from them, as a rule, do not exceed one day, i.e., are within the accuracy limits of the observations. The changes of average dates caused by climatic fluctuations, with calculation of these dates according to a more than 30-year series, do not exceed the error limits of the calculation itself. The coefficient of asymmetry is less accurately determined, but only in very rare cases does the error of its calculation cause an inaccurate calculation of the date with the required frequency rating of more than one day. Comparing dates of an equal frequency rating obtained according to the calculation and plotted from the empirical curve demonstrated that the deviation of these dates in 90 - 95% of the cases do not exceed one day, i.e., do not exceed the observation accuracy limits.

The parameters of the curves of date frequency of the ice phenomena (and the dates of varying levels of frequency themselves) have been summarized in the form of maps for the navigable rivers of the USSR. The maps of average dates (norms) had also been drawn earlier according to more or less detailed data. We shall dwell briefly on the first generalized characteristics of changeability and asymmetry. The mean square deviations from the norm increase for all ice phenomena from east to west, and particularly intensive in the western part of the ETS. Over a greater part of the Territory of the Soviet Union, the change-ability isolines are nearly perpendicular to the isolines of ice phenomena times. This is because the ice phenomena times are decisively influenced by latitudinal zonality (particularly in Spring, when the proportion of solar radiation is high in the thermal balance of the snow-ice surface), and changeability increases in zones of a maritime climate and decreases in zones of the continental climate.

The basic greater asymmetry zones also tend toward the extreme western and southern regions, where the boundary of the stable riparian ice regime runs. Here the Autumn ice formation is occasionally very late and the debacle is sometimes very early. This is responsible for the positive asymmetry of the Autumn ice phenomena and the negative asymmetry of the Spring ones.

Another highly asymmetrical zone is Eastern Siberia. The negative asymmetry of the Spring ice phenomena is particularly significant here. These phenomena occasionally begin significantly earlier than the average times. This is associated with the high influx of heat from solar radiation and the melting of the snow cover long before the river debacle.

Other, secondary characteristics of the geographic distribution of change-ability and asymmetry of the ice phenomena dates are given a basis during a more detailed examination. The parameters of equations of the frequency curves of duration of the period of no ice are associated with parameters of the curves of

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guarantee of termination of the Spring debacle and the appearance of ice, which
are mutually independent, random values.

The identified principle of geographic distribution of the parameters of
the ice phenomena time guarantee curve equations enables one to use the maps
drawn by the author to calculate the guarantee date curves of ice phenomena and
the duration of the period of no ice on stretches of rivers for which observations
are inadequate. In order to test the possible accuracy of such a calculation, the
times of equal frequency rating have been compiled and calculated according to
parameters taken from maps according to interpolation and taken according to the
empirical frequency curve. The probability deviations for the ice phenomena
dates proved to be close to one day and those for the duration of the period of
no ice were about 1.7 days, i.e., comparable to the accuracy of observations.

Calculating the elements of the ice regime of newly built reservoirs has
special significance with the development of hydrotechnical construction on
large navigable primary waterways. The work of I. V. Balashova[1] gives a char-
acterization of the methods and results of calculations of the annual dates of
the onset of icing and clearing the reservoirs from ice. However, when designing
hydrotechnical facilities it is unnecessary to have annual dates in the calcula-
tion - it is adequate to have their frequency curves.

The author used the accumulated data of calculations and observations to
develop a method of calculating the parameters of frequency curves.

The average dates of the onset of icing on a given stretch of the reservoir
can be calculated according to the sums of average daily negative air temperatures
which are necessary for freezing of the reservoir $\Sigma\theta_-$ (7), and the average depth
of the latter, h. It is known from the more detailed investigations (8), that
the indicated sum is strongly influenced by the current speed as well. Therefore,
the author has taken the lower envelope of the graph of relationship $\Sigma\theta_- = f(h)$
as the basis of the calculation, while the deviation in the actual values of
$\Sigma\theta_-$ from it is associated with the average current velocity in a calculated
stretch v. As a result, the following formula was obtained

$$|\Sigma\theta_-| = 6.82\sqrt{h^2 + 4.84} + 175v - 15. \tag{1}$$

The date of accumulation $\Sigma\theta_-$ calculated according to this formula is con-
sidered to be the onset of icing. One can make a calculation according to
formula (1) for stretches of a reservoir located 120 - 150 km below the hydro-
electric station. The formation of icing occurs later on stretches which are
closer to the lower waters of the hydroelectric power plant.

The average dates of ice clearance are determined with the aid of the
relationship of the sum of average daily positive air temperatures $\Sigma\theta+$,
necessary for ice clearance, with the sum of average monthly negative air
temperatures $\Sigma\theta_-$ over the Winter (7), taking into account the effect of the

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[1] See this volume.

stability of the reservoir and the influx of heat from solar radiation at the end of the thaw, which play an important role in the process of ice destruction (3). The flow factor is characterized by the relationship of the volume of water w that flows through the reservoir over the last two ten-day periods of the ice melt with the total volume of the reservoir at the end of its pre-Spring period of evolution, W. The mean daily value of the total influx of solar radiation Q' was determined for the last ten-day period of the ice melt. The calculation formula has the following appearance

$$|\Sigma\theta_+| = 2.5 |\Sigma\theta_-| - 0.2 e^{0.062|\Sigma\theta_-|} - \\ - 53.6 \lg\left(1 + \frac{w}{W}\right) - 0.16Q' + 95. \tag{2}$$

It is valid when $|\Sigma\theta_-| \leqslant 80°$. The date of accumulation of the total of positive average daily temperatures calculated according to formula (2) is taken for the date of reservoir ice clearance.

Changeability and asymmetry of determining dates of the ice phenomena on reservoirs were obtained by comparing their characteristics σ and C_S with those observed on the very same stretches of the rivers before the construction of hydrotechnical facilities according to the comparable date series. It proved that freezing dates for the reservoirs, which usually fall between the dates of the appearance of ice and icing on the river have values of σ and C_S which are intermediate ones; they can be determined by interpolation. In this instance, changeability for a reservoir is a lower value than for a river. For the calculation one takes the average reduction coefficient, which is 0.84. The parameters of changeability and asymmetry for the dates of reservoir ice clearance were very similar to the parameters for dates of termination of Spring icing, which were also taken in the calculation directly.

The duration of the period of the absence of ice is determined by the difference between the dates of the appearance of the ice in the Autumn and clearance from ice in the Spring. The duration of the Spring ice-gang (debacle) on reservoirs is short; for stretches with little current and reservoirs within the hydroelectric power plant cascade, it averages two days. For the upper stretches of "single" reservoirs it averages three days. If one takes this correction into account, then in order to determine the parameters of the equation of the frequency curve of the duration of the ice-absence period, one can use the parameters obtained according to the calculation for dates of the onset of icing (D_I, σ_I, C_{SI}) and clearance from ice ($\bar{D}_C$, σ_C, C_{SC}) of the reservoirs. As was mentioned, these dates are independent statistical values. Therefore, a composite probability is applicable to it and the parameters for the difference ($\bar{T}$, σ_T, C_{ST}) are found with parameters for the initial values in the following relationships (1):

$$\bar{T} = \bar{D}_I - \bar{D}_C. \tag{3}$$
$$\sigma_T^2 = \sigma_I^2 + \sigma_C^2 \tag{4}$$
$$C_{ST} = \frac{1}{\sigma_T^3}(\sigma_I^3 C_{S\,I} - \sigma_C^3 C_{SC}). \tag{5}$$

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Hence, the frequency curves of the times of icing onset, ice clearance, and duration of the period of ice absence can be calculated for newly constructed reservoirs with the presence of only climatic and projective data. A check on the accuracy of the calculation demonstrated that the dates and values of equal frequency (within limits of 10 - 90%) according to the calculated and empirical curves have probability deviations for ice clearance of 1.3 days, 1.6 days for the onset of icing, and 2 days for the duration of the ice-absence period. Such values are fully comparable with the accuracy of determining the times of ice phenomena on reservoirs.

The investigation of spatial and space-time relationship changeability has important significance for studying the general principles of propagation of the ice phenomena and for practical purposes (calculations, and particularly long-term forecasts).

The spatial distribution of the ice phenomena times was first investigated by G. R. Bregman (2), who drew annual maps of deviations from the norm of dates of ice phenomena on rivers of the European territory of the USSR in the beginning of the 1940's. In order to generalize for the entire territory of the Country, it is more expedient to draw maps of the normalized deviation from the norm $\left(\dfrac{D_i - D}{\sigma} \right)$. The examination of such maps for a series of characteristic

seasons has shown that significant anomalies of ice phenomena times encompass rivers of extensive territories, but at the same time, in each season, one invariably traces a significant difference in these anomalies for rivers in different parts of the Country. The quantitative representation of the general principles of spatial distribution of normalized deviations of ice phenomena dates from the average multiannual ones is provided by comparing the "spatial" curves of the frequency of these values with the generalized "time" frequency curve. The author has also plotted curves similar to the way curves were plotted by G. P. Kalinin (5) for the normalized modular coefficients of the annual flow. The general character of the spatial and time curves is similar, i.e., as for the flow, there exists an arbitrary ergodicity of distribution of ice phenomena times, although significant differences do exist in individual years, obviously due to the limitation of area of the examined territory. Thence, the expediency of taking into account the similarity of character of the annual spatial distributions to the generalized time ones during calculations and forecasts is obvious. In order to implement this, regions are determined in which the times of ice phenomena are homogeneous from year to year and principles of relationships between the times of ice phenomena on rivers in different regions have been identified.

Regions were identified according to the sign of the similarity of deviations from the norm in the times of ice phenomena for all stretches of a river in each year within the boundaries of a region[1]. Certainly, the crux of the matter is the rivers for which such generalization is possible, i.e., rivers whose basin

[1] The works of G. R. Bregman, T. N. Makarevich, N. F. Vinogradova and other authors were used during the regional work-up.
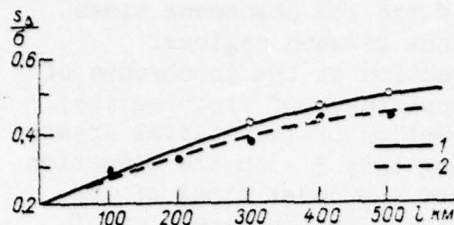
area is at least 10,000 km^2.

Figure 1. Relationship of the normalized square values of deviations in the local and territorial characteristics of ice phenomena times $\frac{s\Delta}{\sigma}$ with the distance between the observation point and the "center of gravity" of the basin 1. 1 - for ice appearance times; 2 - for onset times of the Spring debacle.

The regional territorial characteristic is determined for each season in each region. This is the median value of the times which deviate from the norm, for example, the appearance of ice in the given year in all observation points on rivers of the region (ΔT_p). The difference between deviations from the norm in separate points ΔT_i and the territorial characteristic $\Delta = \Delta T_i - \Delta T_p$ was statistically processed. It proved that large deviations Δ are more frequently observed for stretches of rivers located on the periphery of regions. This is evident from the relationships of the normalized mean square value of deviations $\frac{s\Delta}{\sigma}$ from the distance 1 between the given point and the center of gravity of the region (Figure 1). In meaning, this relationship is similar to the normalized structural function. The minimum value $\frac{s\Delta}{\sigma} = 0.2$ expresses a deviation which does not depend upon the position of the observation point. The very same value of deviation resulting from distance appears when 1 $\approx$ 300 km. This also determines the optimum dimensions of the region - the greatest extent up to 600 km and an area of about 270 - 300,000 km^2. Certainly, such regional dimensions are averaged ones; they change depending upon specific conditions. Thus, in a plain, the regions can be greater than in strongly broken basins; the regions should be smaller in a zone of unstable climate where interruptions in the ice phenomena are frequent, etc.

The symbols on map 62 of the region have been identified taking into account all of the general and specific geographical conditions in the territory of the Soviet Union. The probable value of deviation Δ for these regions is about one day, and consequently, the territorial characteristic reliably reflects the background of ice phenomena times on rivers of the region.

The use of territorial regional characteristics of the freezing and debacle times of rivers in investigations conducted by the method of long-term forecasts of these phenomena has an important advantage: the general conditions of appearance of anomalies relating to ice phenomena times - atmospheric macroprocesses - are associated with the territorially general characteristics of these times for vast territories. It has been established that in order to ensure satisfactory forecasts for all rivers of a region, it is necessary that the forecast relationship identified for the generalized times ΔT_p correspond to the criterion $\frac{S}{\sigma} \leqslant 0.75$. It is necessary to make such an assumption in the effective "rules for the forecast service".
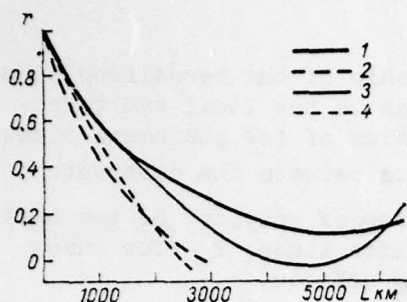
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Figure 2. Relationships of the correlation coefficients of the ice phenomena times with the distance between regions.
1 - in the direction of the isochrones of the times of appearance of floating ice; 2 - in the direction of the spatial appearance of floating ice; 3 - in the direction of isochrones of the onset times of the Spring debacle; 4 - in the direction of propagation of the Spring debacle.

The correlation between the territorial characteristics of these times in different regions was used to investigate principles of the space-time relationships of ice phenomena times in an extensive territory. The values of ΔT_p for pairs of regions located along the isochrones were correlated, i.e., for rivers where the ice phenomena occur, on the average, at similar times, as well as for pairs of regions located in the direction of the propagation of the ice phenomena. Figure 2 shows a measurement of correlation coefficients depending upon the distance between regions.

The graphs primarily show the anisotropicity of the anomaly field of the ice phenomena times. The correlation coefficients diminish proportional to distance, with respect to those located along the isochrones, significantly more slowly than for the similar pairs located in the direction of propagation of the ice phenomena. The cause of this difference is that in the former case the reduction in the correlation coefficient is due to a difference in conditions, chiefly meteorological conditions in space, while in the latter case one adds still the influence of the change in these conditions in time.

Differences in the type of the relationship $r = f(L)$ are also significant for different seasons. The decrease in r proportional to distance occurs more slowly for the times of appearance of ice. A steeper drop in r with distance along the isochrones and a lesser effect of the difference in time are characteristic for the onset times of the Spring debacle.

Still another characteristic is also significant: the type of curve for the Autumn debacle ice phenomena is indifferent with respect to the geographical localization of regions. For the Spring phenomena themselves, the curve $r = f(L)$ drops particularly steeply, falling to significant negative values of r if one region is in the European territory of the USSR and the other is in the Asiatic territory.

Both the general aspects and the specific features of the fields of times of ice phenomena are basically associated with the character of meteorological fields, primarily the air temperature ones. This is confirmed by the similarity of the obtained curves of the relationship $r = f(L)$ with their methodologically similar manner of obtaining the normalized autocorrelation functions of air temperature cited in works of meteorologists (6, and others).

In the final analysis, the type of relationship $r = f(L)$ is determined by

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the scale and seasonal characteristics of atmospheric macroprocesses. Thus, when the dimensions of high crests and troughs in the troposphere are extensive, the zone of identical direction of the transfer from the axis of the depression to the axis of the crest occupies nearly 2 - 3 thousand km. The meaningful correlation coefficient is also conserved at such a distance. With a further increase in distance, the relationship is either fully lost or even becomes an inverse relationship, but at a distance of 5,000 - 7,000 km, i.e., when the drop is into a similar branch of an adjacent deformation field, the correlation coefficients again become positive ones.

In Autumn, the Northern Hemisphere is characterized by the development of a zonal circulation while in Spring it is characterized by enhancement of the meridional one. Therefore, stable contrasts of the anomalies with respect to latitude are not typical for Autumn but they appear frequently in Spring. In this case, both basic forms of meridional circulation (according to Vangengeym and Girs) are characterized by the geographical localization of altitudinal troughs and crests which causes the opposite signs of anomalies in air temperature over the European part of the USSR and Siberia.

14 zones were identified on the basis of this analysis, taking into account the specific geographical conditions - orography, the flow directions of rivers, the alternation time of synoptic seasons - within which a stable relationship exists among the times of ice phenomena ($r \geqslant 0.6$). One can take the original dates of ice phenomena with identical frequency for rivers of each zone in the calculations to back-up the times of navigation and other similar calculations. It is expedient to develop a method of long-term ice forecasts for these rivers based on taking into account the identical characteristics of atmospheric circulation.

The principal character of changes in the correlation coefficients of times of ice phenomena, depending upon the distance and difference in average dates of their appearance among regions can be used in calculations and forecasts. Thus, if a vast deviation of these times from the norm occurs in one of the regions (or is anticipated), one can calculate their most probable deviations from the norm in other regions. These types of calculations can be useful when matching long-term forecasts over an extensive territory.

One can also assign any particular data as initial ones, for example, unfavorable times of ice phenomena in any particular important region with respect to the economic considerations. Accomplished examples of such calculations have shown that their application during navigation planning on rivers encompassing an extensive territory can provide a noticeable savings.

In conclusion, one should note that everything that has been done in the realm of analyzing the statistical structure of fields of ice phenomena times is the first step on the pathway to creating new methods of long-term forecasts based upon the investigation of structural associations between atmospheric and hydrological processes over vast areas.

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CHARACTERISTICS OF THE ICE REGIMES OF RIVERS

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The process of formation of the ice regime of rivers under different climatic and synoptic conditions is realized with the complex interaction of such factors as the inflow of ground water, the water bearing content, extended slopes and the morphology of channels, the convolution and orientation of the river network, human economic activity, etc. One frequently observes peculiarities in the development of ice phenomena along the length of water courses and the methods of their calculation do not practically exist through the present.

It is known that freezing, debacle and build-up in the thickness of ice are the result of heat exchange of the water flow with the environment. Climate plays an important role in this process. The characteristics of certain components of the ice regime of large and medium size rivers were compiled according to the data of observations of water measuring stations (3, 9, and others) (times of debacle and freezing of rivers in the USSR, the ice thickness on rivers in the European part of the USSR, etc.). Investigations carried out by L. G. Shulyakovskiy (10), Ya. I. Marusenko (5), L. G. Glazacheva (1) and other authors showed that in a number of cases the accuracy of such generalizations is inadequate for estimating the ice regime of specific stretches of rivers, particularly small ones. The varying intensity of subterranean in-flow along the length of rivers, variations in the longitudinal slopes and the convolution of the channel, which determine the low velocity regime, as well as other factors lead to a large territorial changeability in the times of onset of different ice phenomena and the thickness of the ice cover.

The author developed a method of determining characteristics of the ice regime for stretches of rivers that had not been covered by hydrological observations based on the example of small rivers of the middle Volga area (7). The method includes calculating the components of the thermal balance and plotting graphic relationships, analyzing the geographic distribution of causative factors, mapping characteristics of the ice regime, and checking the calculation data by means of full-scale observations.

The intensity and developmental trend of the ice processes are determined by the relationship of heat losses and heat influx. Heat losses (heat exchange by convection, evaporation and the radiation balance) are derivatives of meteorological conditions and change throughout the territory in accordance with the geographic zonality. The components of heat influx (the heat of subterranean water, from dissipation of flow energy), on the contrary, are chiefly determined by azonal factors. Therefore, their territorial (and length-wise with respect to rivers) distribution is extremely uneven.

Heat losses, as well as the heat of energy dissipation, were calculated according to a method presented in the work of R. V. Donchenko (2). The mean multiannual values of heat losses from the water's surface under conditions of the middle Volga area are 250 - 800 cal/(cm^2 · day) in November - February.

4.4

Determination of the amount of heat supplied with subterranean water on a given stretch is a complicated task in most cases because of the difficulty of calculating the subterranean supply. L. G. Shulyakovskiy (10) assumed that the single method of determining the in-flow of subterranean water to rivers is comparing the flow rates of water or the flow volumes over a certain span of time on two stretches located at the beginning and end of the investigated stretch. The location of the stretches is usually predetermined by the hydrological stations, which are located at distances of tens and hundreds of kilometers apart, as a rule. The Shulyakovskiy calculations for the Volga and certain of its tributaries demonstrated that the specific influx for both large and small rivers averages $3.0 - 6.0$ cm^3/day per 1 cm^2 of water surface.

It should be pointed out that the specific influx along the length of the river is very unequal and on small rivers this inequality is more strongly pronounced than on large ones. For example, on the Kazanka River, whose length became approximately 150 km following the construction of the Kuybyshev reservoir, the average value of the subterranean influx comprises approximately 6.0 cm^3/cay and on certain stretches ranges from 0 to 400 cm^3/day and more per 1 cm^2 of water surface (Table 1). Therefore, at individual points on this river the formation of the ice regime occurs without being influenced by the heat of subterranean water while in other places the influx of heat exceeds 200 cal/day per 1 cm^2 and the ice cover does not form at all.

Experience in investigating the characteristics of the ice regime of middle Volga rivers has shown that a realistic evaluation of the ice phenomena along stretches of the river requires differential data about the influx of subterranean water, and not data averaged over its entire length (or a significant part of it). In order to determine the magnitude of subterranean supply and to clarify its role in the formation of characteristics of the ice regime, the author used the material of a hydrometric survey of rivers. The method of making the survey is presented in a study (6). It was noted in 1965 at an interdepartmental seminar conducted in June at the GGI that the hydrometric survey, in combination with the hydrogeological analysis, is a reliable method of estimating the subterranean flow in the river. The latter is calculated according to the increments in the average multiannual low-water level flow rates of water between the tributaries or the influx and the water monitoring station. One calculates the specific influx of subterranean water γ (cm^3/day per 1 cm^2) on the stretches according to the following relationship

$$\gamma = \frac{86.4 \cdot 10^5 q}{s},$$

where q is the influx of subterranean water on the stretch, m^3/sec; s is the area of the water surface on the stretch, m^2.

Table 1 gives the results of calculating the specific in-flow of subterranean water on stretches of the Kazanka River. Similar calculations were made for most rivers of the middle Volga area and a map of changes in the specific in-flow along their length was drawn (5). This map serves as the primary source for identifying stretches with particular conditions of development of the ice phenomena. High values of the specific in-flow magnitudes are most often encountered on rivers up to 50 km long (Table 2), particularly in their upper water areas located within the confines of the Vytsko-Kama, the near-Volga and Bugul'mino-Belebeyevsk highlands.

Таблица 1

Удельный приток подземных вод по длине р. Казанки

Участок осреднения	Длина участка, км	Ширина реки, м	Площадь зеркала, м²·10⁻³	Приток подземных вод, м³/с	Удельный приток, см³/(см²·сутки)
Исток — родник Апайкино	6,6	—	—	0,000	0,0
Родник Апайкино — 1-й левый приток (л. пр.)	0,2	0,5	0,1	0,009	778,0
1-й л. пр. — 2-й правый приток (пр. пр.)	0,1	0,7	0,1	0,000	0,0
2-й пр. пр. — 4-й л. пр. (Урняк)	4,2	0,8	3,3	0,002	5,2
4-й л. пр. — 5-й пр. пр. (Пшалым)	1,5	1,9	2,8	0,040	123,0
5-й пр. пр. — 6-й пр. пр. (Метеска)	13,2	3,5	46,2	0,180	34,0
6-й пр. пр. — 7-й л. пр. (Кисьмесь)	2,6	5,0	13,0	0,000	0,0
7-й л. пр. — 8-й л. пр. (Чекурча)	1,8	8,0	14,4	0,000	0,0
8-й л. пр. — водпост Арск	3,8	8,0	30,4	0,005	1,4
Водпост Арск — 10-й пр. пр. (Верези)	3,4	7,0	23,8	0,000	0,0
10-й пр. пр. — 11-й л. пр. (Чулпаново)	9,1	8,0	72,8	0,052	6,2
11-й л. пр. — 12-й пр. пр. (Субаш-Аты)	8,7	9,0	78,3	0,030	3,3
12-й пр. пр. — 14-й л. пр.	14,4	10,0	144,0	0,940	2,4
14-й л. пр. — водпост Куркачи	1,1	10,0	11,0	0,000	0,0
Водпост Куркачи — 15-й пр. пр. (Красная)	1,6	10,0	16,0	0,030	16,0
15-й пр. пр. — 19-й пр. пр. (Серда)	22,1	12,0	265,2	0,650	21,0
19-й пр. пр. — водпост Бимери	7,1	13,0	92,3	0,060	5,6
Водпост Бимери — 21-й пр. пр. (Сула)	8,6	13,0	111,8	0,050	3,9
21-й пр. пр. — 24-й л. пр.	7,8	14,0	109,2	0,050	4,0
24-й л. пр. — 25-й л. пр. (Киндерка)	11,4	14,0	159,6	0,040	2,2
25-й л. пр. — 26-й пр. пр.	5,8	14,0	81,2	0,400	4,2
26-й пр. пр. — 27-й пр. пр.	2,3	17,0	39,1	0,600	130,0
27-й пр. пр. — 28-й пр. пр. (Солонка)	0,7	19,0	13,3	0,700	460,0
28-й пр. пр. — 29-й л. пр.	4,1	21,0	86,1	0,070	7,0
29-й л. пр. — водпост Большие Дербышки	0,3	21,0	6,3	0,090	120,0
Водпост Большие Дербышки — 31-й л. пр. (Нокса)	2,7	21,0	56,7	0,000	0,0

Примечание. Участки расположены между устьями непересыхающих притоков, в скобках — названия последних.

(Note: commas should be read as decimals.)

Key:

1 - Table 1. Specific Influx of Subterranean Water Along the Length of the Kazanka River.
2 - Averaging stretch
3 - Length of stretch, km

continuation of key for Table 1:

4 - Width of stretch, m
5 - Mirror area, $m^2 \cdot 10^{-3}$
6 - Influx of subterranean water, m^3/sec
7 - Specific influx, $cm^3/(cm^2 \cdot day)$
8 - Source - Apaykino spring
9 - Apaykino spring - first left tributary (left tributary)
10 - First left tributary - second right tributary (right tributary)
11 - Second right tributary - fourth left tributary (Urnyak)
12 - Fourth left tributary - fifth right tributary (Pshalym)
13 - Fifth right tributary - sixth right tributary (Meteska)
14 - Sixth right tributary - seventh left tributary (Kis'mes')
15 - Seventh left tributary - eighth left tributary (Chekurcha)
16 - Eighth left tributary - Arsk water station
17 - Arsk water station - tenth right tributary (Verezi)
18 - Tenth right tributary - eleventh left tributary (Chulpanovo)
19 - Eleventh left tributary - twelfth right tributary (Subash-Aty)
20 - 12th right tributary - 14th left tributary
21 - 14th left tributary - Kurkachi water station
22 - Kurkachi water station - 15th right tributary (Krasnaya)
23 - 15th right tributary - 19th right tributary (Serda)
24 - 19th right tributary - Bimeri water station
25 - Bimeri water station - 21st right tributary (Sula)
26 - 21st right tributary - 24th left tributary
27 - 24th left tributary - 25th left tributary (Kinderka)
28 - 25th left tributary - 26th right tributary
29 - 26th right tributary - 27th right tributary
30 - 27th right tributary - 28th right tributary (Solona)
31 - 28th right tributary - 29th left tributary
32 - 29th left tributary - Bol'shiye Derbyshki water station
33 - Bol'shiye Derbyshki water station - 31st left tributary (Noksa)
34 - Note. The stretches are located between the mouths of permanent tributaries,
   the parentheses enclosed names designate the latter.

At the same time, in the lower water stretches of comparatively large rivers such
as the Ilet', Kazanka, the Sviyaga and others as well, in places one observes
very high values of the subterranean in-flow which exceed 100 cm^3/day per 1 cm^2
of water surface. These tend toward the stretches where the copious water-bearing
strata of the Kazan' and Cretaceous deposits drain.

When Table 2 was being compiled, rivers of the investigated region were grouped
according to the cited gradations of length. Within the limits of each gradation
the number of stretches with the assigned values of the specific in-flow of sub-
terranean water was counted.

The amount of heat supplied with the subterranean water is equal to the
product of the value of their in-flow and water temperature. On the basis of
observations made by the author and investigations carried out by V. V. Piotrovich
(8), a temperature of $6^{\circ}C$ was accepted as the calculated one.

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1 Повторяемость различных значений удельного притока подземных вод
на реках Среднего Поволжья

Удельный приток, **2** см³, сутки на 1 см²	**3** Повторяемость (%) величин удельного притока на реках длиной				
	4 до 20 км	21—50 км	51—100 км	101—200 км	201—500 км
0—10	31	60	72	83	86
11—20	20	16	14	12	10
21—30	17	11	6	2	2
31—40	12	5	2	1	0
41—50	8	2	3	1	0
51—75	7	3	1	0	0
75—100	2	1	0	0	1
>100	3	2	2	1	1
5 Итого	100	100	100	100	100

Key for Table 2:

1 - Table 2. The Repetition of Different Values of the Specific In-flow of
    Subterranean Water on Rivers of the Middle Volga Area
2 - specific inflow, cm^3/day per 1 cm^2
3 - repetition (%) of values of specific in-flow on rivers of the following
    lengths
4 - up to 20 km
5 - Total

The influx of heat with subterranean water along stretches of the river ranges
from 0 to 5,000 cal/cm^2.

Because of the dissipation of flow energy, the heat influx fluctuates within
limits of 0.0 - 50.0 cal/(cm^2 · day), while the heat influx from the river channel
soil averages 20 cal/cm^2 · day. The total heat influx with the subterranean water,
from the dissipation of flow energy and from flow channel soil on different stretches
of rivers fluctuates, therefore, from 20 to 5,000 cal/(cm^2 · day).

The times and character of freezing of different river stretches depend on
the total influx of heat and the slopes, as well as the flow rate of water. These
factors usually change little in time, but are very unequally distributed along
the length of rivers. Graphs which enable one to determine the dates of the
appearance of ice and freezing of individual stretches of rivers and which take
these factors into account according to the transition of the mean daily temp-
erature of the air through $0°C$, are cited in a study (4).

In specific years, the characteristics of freezing of stretches of rivers
are determined by the synoptic-meteorological conditions. When there is an
intensive increase in negative temperatures, the sums of thermal losses build-
up rapidly and universally, and therefore differences in the times of freezing
of rivers of the middle Volga area do not exceed 5 - 10 days. On the other hand,
the frequent alternation of air masses and the unstable negative air temperatures
cause differences in freezing times of up to 1.5 - 2.0 months through the given
territory and along the length of the rivers.

The thickness of the ice cover depends upon the sum of negative air temperatures over the period of ice build-up and the build-up in the specific heat influx from water (see the figure).

According to the data of the author's investigation and on the basis of material in the literature and on background, one can establish the following conditions of ice formation on rivers:

a) rapids stretches or stretches with a specific heat influx in excess of 500 cal/(cm^2 · day) do not freeze;

b) stretches with slopes of 1 - 5% and a specific heat influx in excess of 100 cal/(cm^2 · day) are characterized by unstable icing with stretches of open water and ice crusts;

c) in places that have snow slides as well as stretches without tributaries, which are quite long and have flow rates of water less than 1.0 m^3/sec, ice crusts whose thickness reaches 1.5 m form (for example, the Tumbarlinka River);

d) on marshy stretches of the river channel the ice thickness is usually 1.5 - 2.0 times less than on stretches of water; in individual cases stretches of water free of ice form (the tributaries of the Shoshmy River); the ice is turbid and contains a great deal of air and organic material;

e) the discharge of warm waste leads to the formation of stretches of water that are free of ice and non-freezing stretches (the Ik River below the Urussinsk combined heat and power plant), while non-uniform releases from reservoirs favor the formation of ice crusts (the Staryy Zay River below Karabash).

*River debacles are characterized by the following features:*

a) stretches with unstable ice phenomena become clear of local ice a month before the background times;

b) stretches of rivers with an unstable ice cover, in which the heat influx with subterranean water exceeds 200 cal/(cm^2 · day) and whose longitudinal slopes are greater than 10/00 undergo debacle 1 - 2 weeks before the background times;

c) rivers whose water flow rates are no more than 1.0 m^3/sec with a low ice thickness or under the conditions of predominance of southern exposure of the slopes undergo debacle 2 - 3 days before the background times. The very same rivers with thick ice crusts and a predominantly northern slope exposure, on the contrary, undergo debacle 2 - 3 days later than the background times;

d) on small rivers, particularly in the presence of ice crusts, the ice melts in place or one observes a rare debacle at flood time. When there is intensive soil erosion the ice crusts become mud caked and the ice in these places occasionally remains until June;

e) on stretches of rivers whose convolution factor exceeds 1.8, in channel narrows, on branched stretches and in zones of reservoir pressure tapering, ice jams systematically form.
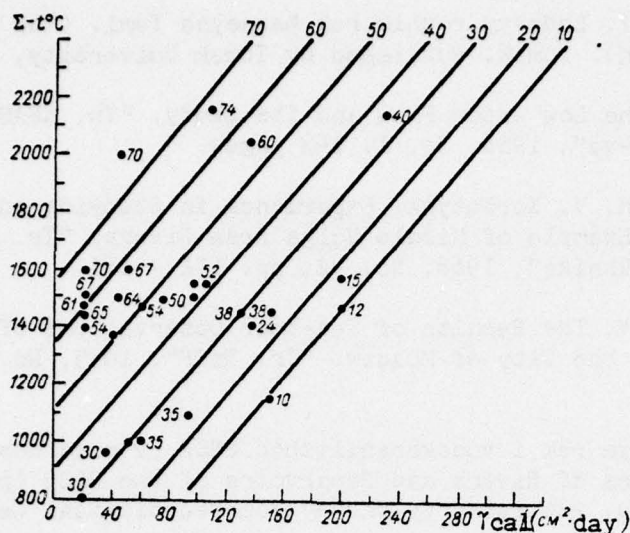
The relationship of ice thickness with the sum of negative air temperatures $\Sigma - t^{\circ}C$ and the specific heat influx from water γ. The numbers next to the points are values of observed ice thicknesses, cm.

Freezing maps, ice thickness maps and debacle maps of rivers of the middle Volga area were drawn on the basis of all material (4, 7). For purposes of clarity, the dates of ice set-in, the length of the period of ice formation, etc. are shown on maps along the rivers. The types of ice phenomena, the thickness of ice at the end of Winter, places of formation of ice crusts and stretches of open water, ice jams and ice dams, debacle dates, and the duration of the debacle are also shown. The reliability of the depicted characteristics was checked by observations at water stations and on monitoring stretches during the ice surveys. Deviations of dates of the onset of ice phases from those cited usually do not exceed 1 - 3 days, while the locations of ice crusts, stretches of open water and unfrozen stretches, the formation of ice jams and ice dams, coincide as a rule.

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THE USE OF DISCRIMINANT ANALYSIS FOR LONG-TERM FORECASTING OF AUTUMN ICE
PHASES IN THE LOWER REACHES AND MOUTHS OF RIVERS IN THE ARCTIC ZONE OF SIBERIA

By: Yu. V. Nikolayev, G. Ye. Usankina

(AANII, Leningrad)

Many branches of the national economy (inland transport, hydroenergetics,
the forestry industry, and others) are interested to one degree or another in
knowing the freezing times of streams, in connection with which the ice regime
of rivers and the study of the principles which cause fluctuations in these
dates in time and space are extremely pressing ones. It is known that the
freezing times of rivers are affected by various factors in combination and the
contribution of each of these factors to the general course of the process is
non-uniform. Therefore, the identification of individual factors that have the
greatest effect on the predicted process is one of the primary problems that
arises during the development of forecast systems.

Investigations of the ice regimes of rivers in the Arctic zone of Siberia
have been carried out at the AANII since 1933 by A. P. Burdykina, who examined
macrocirculation atmospheric processes in detail. Such processes affect the
freezing times of rivers (2, and others). In analyzing the multiannual fluc-
tuations of ice formation dates, Burdykina concluded that the background of the
forecasted phenomenon is determined by the predominant types of atmospheric
circulation over the investigated territory (according to Vangengeym). Burdykina
suggested forecast relationships of freezing times with some particular char-
acteristic of atmospheric circulation. The conclusion that atmospheric pro-
cesses have a significant effect on freezing of rivers in the Arctic zone of
Siberia was confirmed by an analysis of the spatial statistical structure of
the ice formation date fields, which have a significant (about 1,000 km) scale.

The purpose of this study was to improve the existing methods of forecasting
the ice regime of Siberian rivers. For this purpose, the effect of macrocircu-
lation processes of the atmosphere on the freezing times of lower reaches and
mouths of rivers in the Ob'-Yenisey region was examined. The pressure field
over the Northern Hemisphere from 40° north latitude and further to the north
was used as the circulation index.

In order to solve the task of the investigation, a method of discriminant
analysis of the atmospheric pressure fields was used.

The method of discriminant analysis had also been used before for fore-
casts of hydrometeorological phenomena (1, 3, and others). In 1966, N. A.
Bagrov (1) predicted the mean monthly amount of precipitation according to
air temperature fields, represented with the aid of discriminant analysis in
the form of coefficients of linear expansion. In 1969, Yu. V. Nikolayev obtained
forecast equations for pre-calculation of the total icing of the Arctic Ocean
in August as the result of a separate analysis of the air pressure and air
temperature fields over the Northern Hemisphere.

This investigation included the following: 1) the identification of opti-
mum regions in which the atmospheric processes most affect the freezing times
of rivers; 2) the identification of data on pressure in optimum regions of

informative forecasts, representing comparatively small numbers of points from the archives.

The identification of optimum regions from the predictor fields was carried out on the basis of analyzing the value d_i^{*2} ($i = 1, 2, \ldots, n$), which characterizes the distance between classes along the axis of the coordinates of the n-dimensional space. For this purpose, the predictor fields were divided into classes in accordance with the classes of the forecasted phenomenon "above the norm" and "below the norm". In the presence of two classes, the value d_i^{*2} is calculated according to the following formula

$$d_i^{*2} = \overline{P}_i^2(A) + \overline{P}_i^2(B) - 2\overline{P}_i(A)\,\overline{P}_i(B),$$

where A and B are classes of the atmospheric pressure fields.

The maximum square of distance between classes d_i^{*2} indicates the highest information content of the given point in space. In order to exclude the effect of air pressure dispersion, it is expedient to use the relationship $\dfrac{d_i^{*2}}{\sigma_i^2}$ for the analysis, where σ_i^2 is dispersion at the i-th point.

The task of identifying the informative predictions using discriminant analysis is analogous to the task of expanding fields according to the natural orthogonal component, during which the first variables $P_1, P_2, \ldots, P_n$ were represented in the form of secondary variables $P_1', P_2', \ldots, P_n'$ as the result of a linear transform, where

$$P_i' = \sum_{i=1}^{n} u_i P_i.$$

The difference between the separate analysis and expansion of the fields according to the natural orthogonal component consists in the modes of determining the transform coefficients u_i ($i = 1, 2, \ldots, n$). As was shown in a study (3), during discriminant analysis the determination of the optimum coefficients is associated with solving the following equation

$$|R^* - \lambda R|\, u = 0,$$

where R^* is a matrix characterizing the differences between classes; R is a covariation matrix for the entire set; u is the eigen vector; λ is the eigen value.

The elements of matrix r_{ij} were calculated according to the following formula

$$r_{i,j} = (N-1)\sum_{k=1}^{N} \overline{P_{ik} P_{jk}} - \sum_{k=1}^{N}\sum_{q=1}^{N} \overline{P}_{ik}\overline{P}_{iq},$$
$$k \neq q,$$

where N is the number of classes by which the information about the predictant is divided.

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The original information was represented by values of the mean monthly pressure at 27 points over the period from 1935 through 1968 (Figure 1). The dates of onset of stable ice formation of rivers in the Ob'-Yenisey region served as the characteristic of freezing times.

The relationships $\dfrac{d_i^{*2}}{\sigma_i^2}$ obtained for each month were averaged by seasons (Fall, Winter, Spring, Summer). A series of points with maximum values of $\dfrac{d_i^{*2}}{\sigma_i^2}$ was chosen to identify the optimum regions for each season. The other points were excluded from the analysis.

The original information about pressure in the optimum regions obtained by linear orthogonal transform was represented in the form of the first expansion coefficients $P_i^!$ for each month (September - December of the preceding year and January - August of the current year).

Figure 2 shows the curve of correlation coefficient moduluses r between the obtained predictions and the onset dates of stable icing. Data on the information content of the predictions for individual months can already be obtained according to the value of the first eigen values λ, whose course coincides basically with the course of value r.

However, the use of one month alone for forecasting the predictors can lead to significant errors and it is therefore more expedient to construct forecast diagrams using several predictors. In this connection, regression equations (see the table) were compiled which make it possible to give forecasts with a timeliness factor ranging from 1 to 11 months.
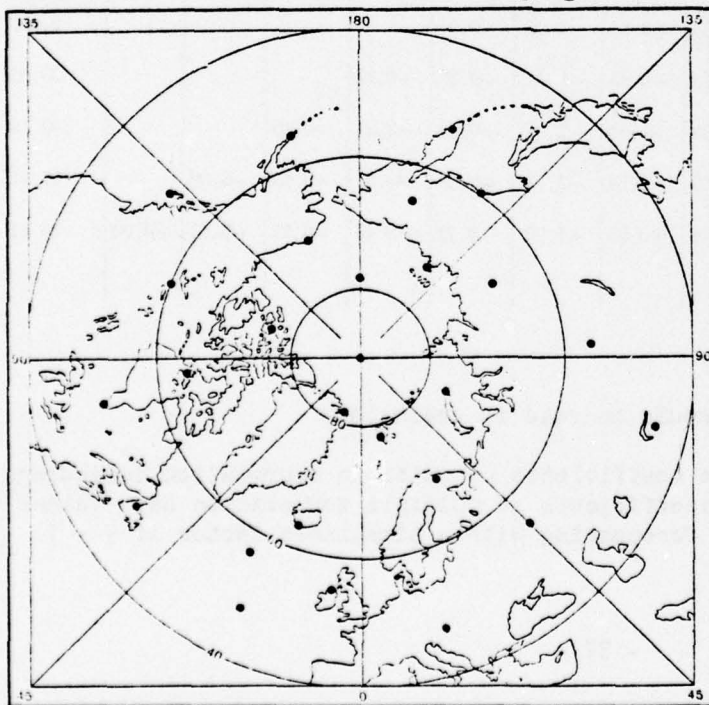

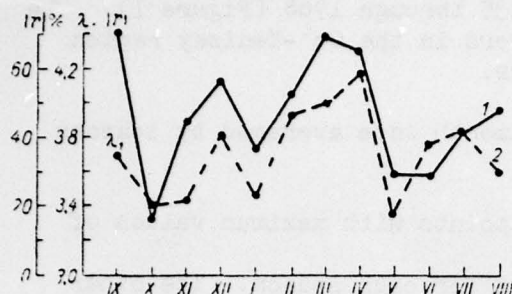Figure 1. Diagram of points used during discriminant analysis of pressure fields.

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Figure 2. Moduluses of correlation co-efficients r between the dates of stable icing and the predictor P' (1) and the first eigen values λ_1 (2).

Coefficients of Regression Equations

Timeliness, months	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	Free Member of Equation
11	−3.24	+0.24											35.55
10	−2.88	+0.25	−0.78										32.68
9	−2.02	−1.41	−1.00	−1.33									25.02
8	−1.87	+0.33	−0.80	−1.41	−0.85								35.59
7	−1.72	+0.30	−0.61	−1.28	−0.67	+0.86							32.17
6	−1.40	−0.20	−0.46	−0.89	−0.32	+0.82	−1.67						27.67
5	−1.22	+0.37	−0.48	−0.94	−0.33	+0.84	−1.96	−0.03					29.61
4	−1.45	−0.39	−0.51	−1.01	−0.33	+0.88	−1.82	−0.32	−0.27				25.62
3	−1.07	+0.34	−0.40	−1.07	−0.30	+1.04	−2.08	+0.22	−0.24	−0.46			30.74
2	−1.12	+0.26	−0.25	−1.00	−0.50	+0.70	−2.13	+0.08	−0.31	−0.40	−0.69		37.81
1	−1.29	−0.54	−0.31	−1.15	−0.56	+0.65	−1.90	−0.12	−0.48	−0.55	−0.81	+0.60	13.61

(Note: commas should be read as decimals.)

Figure 3 shows changes in the coefficients of multiple correlation depending on the forecast timeliness. The coefficients of multiple correlation have values of greater than 0.80 already when forecasting with a timeliness factor of 9 - 7 months.

The regression equations, which make it possible to predict the dates of stable ice formation of rivers in the Ob'-Yenisey region with a timeliness factor of 8 and 7 months were verified using independently obtained material covering 4 years (1969 - 1972). The estimate was made according to two 0.20 A criteria (amplitudes) and 0.674 σ. The verification forecasts were valid according to both criteria.
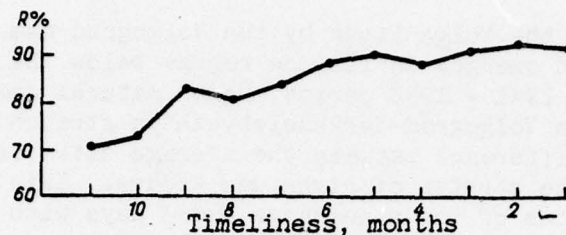

Figure 3. Change in the coefficients of multiple correlation of regression equations depending on forecast timeliness.

Hence, optimum regions were determined as the result of discriminant analysis of pressure fields over the Northern Hemisphere and then the most informative predictors of the ice formation dates of lower reaches and mouths of rivers in the Ob'-Yenisey region were identified. The predictors served as the basis for compiling the regression equations. Forecasts have been given according to the obtained equations on the basis of an independently obtained material. Such forecasts were totally valid.

Of course, four years do not enable one adequately fully to judge the validity of the method, but taking into account the quite high coefficients of multiple correlation, one can assume that the given forecast systems are promising.

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THE EFFECT OF THE VOLGOGRAD RESERVOIR ON ICE APPEARANCE DATES AND THE DURATION
OF DEBACLE ON THE VOLGA RIVER BELOW VOLGOGRAD AND IN THE VOLGA DELTA

By: A. K. Barabash

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The flow regulation of the Volga River by the Volgograd dam (hydrotechnical
facility) caused significant changes in its ice regime below the city of Volgograd
and in the delta. Over the 1941 - 1958 period, under natural conditions, floating
ice appeared in the northern Volgograd-Verkhnelebyazh'ya stretch and extended to
the south (Table 1). The difference between the average dates of ice appearance
in the north and south of the stretch of river was 4 days. This difference com-
prised 7 days with early dates of ice appearance and 3 days with later ones.

In the delta the ice usually forms earlier on the eastern streams, and then
on the Bakhtemir stream. The earliest ice appearance on the eastern streams is
explained by the fact that the flow rates are lower in them than in the Bakhtemir
stream.

Under conditions of regulation of the Volga flow by the Volgograd dam (accord-
ing to data for 1959 - 1972), floating ice appears in all cases to the south of
the examined stretch. The difference in average dates of ice appearance between
the south and north of this stretch of the river comprises 3 days. The difference
for the early dates is 4 days and is 2 days for the later ones. The sequence of
dates is conserved in the delta.

The average multiannual ice appearance date under natural conditions in the
Chernyy Yar following the average multiannual date of air temperature transition
via $0^{\circ}C$ to negative values is 7 days later, is 11 days later at Astrakhan', and
6 days later at Zelenga. The average date of ice appearance over the 1959 -
1972 period is 25 days later than the average multiannual date of air temperature
transition through $0^{\circ}C$ to negative values at Chernyy Yar, 23 days later at
Astrakhan', and 17 days later at Zelenga.

Taking into account the fact that over the 1959 - 1972 period the transition
of average daily air temperature through $0^{\circ}C$ to negative values was later, on
the average, than the multiannual dates at Chernyy Yar by 13 days, by 11 days at
Astrakhan', and 8 days at Zelenga, one can consider that the ice appears later
at Chernyy Yar as the result of the warming effect of the Volgograd reservoir
than under natural conditions, averaging 5 days there and 1 - 3 days in the delta.

The warming effect of the reservoir is well noticeable according to the
empirical relationships $\Sigma\Theta- = f\ (\vartheta_0)$, where $\Sigma\Theta-$ is the sum of negative air
temperatures from the date of air temperature transition via $0^{\circ}C$ to the date
of ice appearance; ϑ_0 is the temperature of the water immediately before the
air temperature crosses $0^{\circ}C$ to negative values according to the corresponding
station on the stretch of river. The relationships have been compiled according
to observational data at stations called the Chernyy Yar, Verkhnelebyazh'ye,
Astrakhan' and Zelenga over the period from 1941 through 1972 (see the figure).

1 Даты появления плавучего льда на участке р. Волги Волгоград—Верхнелебяжье и в ее дельте в естественных и зарегулированных условиях

Река, рукав 2	Пункт 3	4 Дата появления плавучего льда					
		5 естественные условия			6 зарегулированные условия		
		7 ранняя	8 средняя	7 поздняя	7 ранняя	8 средняя	9 поздняя
Волга 10	Волгоград 16	8/XI	23/XI	13/XII	23/XI	16/XII	27/XII
	Черный Яр 17	9/XI	24/XI	16/XII	19/XI	12/XII	24/XII
	Енотаевск 18	8/XI	25/XI	17/XII	20/XI	8/XII	23/XII
	Верхнелебяжье 19	15/XI	27/XI	16/XII	19/XI	13/XII	25/XII
	Астрахань 20	10/XI	4/XII	27/XII	22/XI	16/XII	29/XII
Бузан 11	Красный Яр 21	9/XI	26/XI	14/XII	19/XI	11/XII	29/XII
Бахтемир 12	Икряное 22	9/XI	29/XI	26/XII	22/XI	14/XII	29/XII
	Оля 23	14/XI	4/XII	26/I	21/XI	15/XII	13/I
Камызяк 13	Камызяк 24	15/XI	28/XI	20/XII	19/XI	10/XII	12/I
Зеленга 14	Зеленга 25	8/XI	1/XII	25/XII	19/XI	12/XII	25/XII
Никитинский банк 15	Караульное 26	15/XI	28/XI	16/XII	20/XI	15/XII	11/I

Key for Table 1:

1 - Table 1. Dates of Appearance of Floating Ice on a Stretch of the Volga River Between Volgograd and Verkhnelebyazh'ye and in the Volga Delta Under Natural and Regulated Conditions
2 - river, tributary
3 - point
4 - date of appearance of floating ice
5 - natural conditions
6 - regulated conditions
7 - early
8 - medium
9 - late
10 - Volga
11 - Buzan
12 - Bakhtemir
13 - Kamyzyak
14 - Zelenga
15 - Nikitinskiy bank
16 - Volgograd
17 - Chernyy Yar
18 - Yenotayevsk

continuation of key for Table 1:

19 - Verkhnelebyazh'ye
20 - Astrakhan'
21 - Krasnyy Yar
22 - Ikryanoye
23 - Olya
24 - Kamyzyak
25 - Zelenga
26 - Karaul'noye
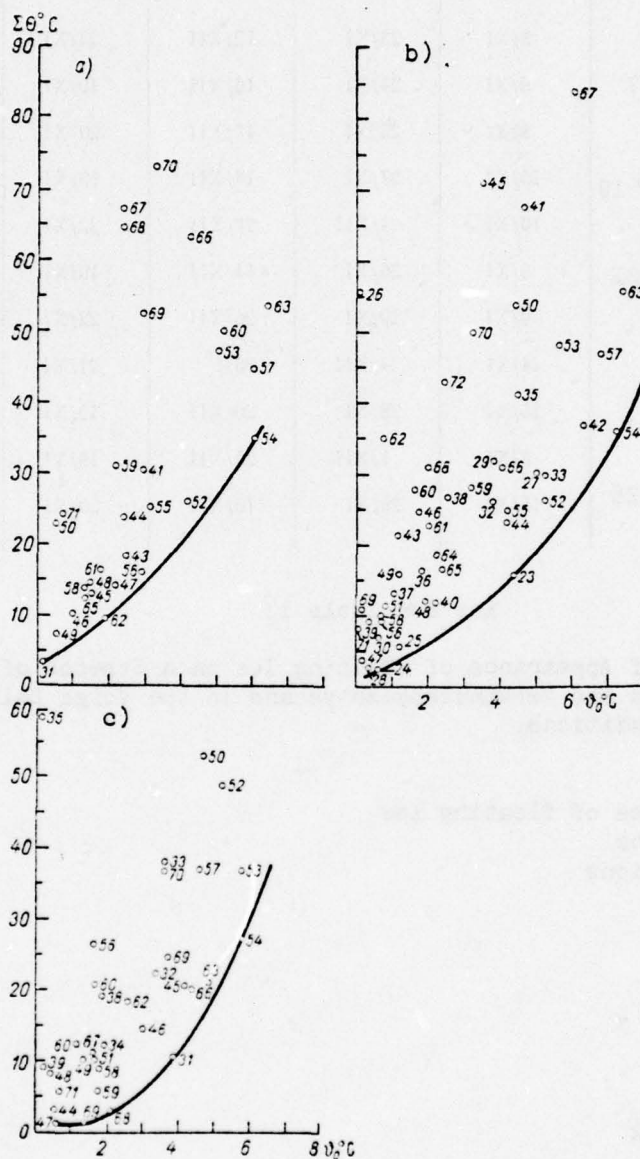
The relationship of the sum of average daily negative air temperatures ΣΘ-, necessary for the appearance of floating ice with the initial water temperature ϑ_0.

a - Chernyy Yar, b - Astrakhan', c - Zelenga. The numbers next to the points are years.

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A greater sum of negative air temperatures is necessary in the relationship for Chernyy Yar in most cases for ice to appear when the water temperature is identical immediately before the air temperature crosses $0^\circ C$ in years with a regulated flow. The difference between the sums of negative air temperatures necessary for the appearance of ice in regulated flows and under natural conditions is less for Verkhnelebyazh'ye than at Chernyy Yar, and is less for Astrakhan' than for Verkhnelebyazh'ye. There is no difference in the temperature totals for Zelenga.

Hence, the warming effect of the Volgograd reservoir gradually decreases proportional to distance from the dam downstream. In the lower reaches of the delta its effect totally vanishes.

Calculation of dates of ice appearance for Chernyy Yar, Yenotayevsk, Astrakhan', Krasnyy Yar, Ikryanyy and Kamyzyak were made for years with a regulated flow according to the method of L. G. Shulyakovskiy[1]. In all 60 cases, the calculation errors did not exceed 1 - 2 days.

On the Volgograd-Verkhnelebyazh'ye stretch, under natural conditions and under conditions of regulated flow, the duration of icing decreases from north to south, while in the delta it decreases from the southwest to the northeast (Table 2). The average duration of debacle under regulated conditions near Volgograd and Chernyy Yar is 6 days greater than under natural conditions, while on the Yenotayevsk-Verkhnelebyazh'ye stretch and in the delta it is practically the same as under natural conditions.

The longest duration of debacle under natural and regulated conditions is observed in years with a westerly movement of the air masses. The shortest duration of debacle is caused by cold air mass penetrations from the Barents and Kara Seas.

A shorter duration of the ice gang than under conditions of regulated flow corresponds to identical totals of negative average daily air temperature near Chernyy Yar. An identical duration of the ice gang corresponds to a similar total near Astrakhan' under natural and regulated conditions.

Hence, the warming effect of the reservoir affects the duration of the ice gang on the stretch of river from Volgograd to Chernyy Yar but is not reflected in the delta.

In Autumn, navigation is practically terminated with the beginning of ice gang formation. Under natural conditions on the Volgograd-Astrakhan' stretch the closure of navigation occurred on 24/XI, when the ice gang near Volgograd began, on the average. Under conditions of regulated flow, navigation terminated, on the average, on 13/XII, when the ice gan began to form at Verkhnelebyazh'ye.

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[1]Shulyakovskiy, L. G. Poyavleniye l'da i nachalo ledostava na rekakh, ozerakh i vodokhranilishchakh (raschety dlya tseley prognozov). (The Appearance of Ice and the Beginning of Icing on Rivers, Lakes, and Reservoirs (Calculations for Forecast Purposes)). Moscow, Gidrometeoizdat, 1960. 216 pages.

Таблица 2

Продолжительность осеннего ледохода на участке р. Волги Волгоград — Верхнелебяжье и в ее дельте в естественных и зарегулированных условиях

Река, рукав	Пункт	Продолжительность осеннего ледохода, дни					
		естественные условия			зарегулированные условия		
		максимальная	средняя	минимальная	максимальная	средняя	минимальная
Волга	Волгоград	46	29	11	>70	35	14
	Черный Яр	51	21	7	62	27	5
	Енотаевск	32	12	0	42	9	1
	Верхнелебяжье	46	12	0	23	11	5
	Астрахань	26	8	0	38	7	1
Бузан	Красный Яр	45	5	0	14	7	0
Бахтемир	Икряное	64	12	2	35	16	4
	Оля	45	14	2	33	14	11
Камызяк	Камызяк	44	8	0	42	11	0
Зеленга	Зеленга	65	10	0	21	10	1
Никитинский банк	Краульное	52	11	0	25	10	1

Key for Table 2:

1 – Table 2. Duration of the Autumn Ice Gang on a Stretch of the Volga River at Volgograd-Verekhnelebyazh'ye and in the Volga Delta Under Natural Conditions and Conditions of Regulated Flow
2 – river, tributary
3 – station
4 – duration of Autumn ice gang, days
5 – natural conditions
6 – maximum
7 – medium
8 – minimum
9 – regulated conditions
10 – Volga
11 – Buzan
12 – Bakhtemir
13 – Kamyzyak
14 – Zelenga
15 – Nikitinskiy bank
16 – Volgograd
17 – Chernyy Yar
18 – Yenotayevsk
19 – Verkhnelebyazh'ye
20 – Astrakhan'
21 – Krasnyy Yar
22 – Ikryanoye
23 – Olya
24 – Kamyzyak
25 – Zelenga
26 – Kraul'noye

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Hence, over the 1959 - 1972 period, the closure of navigation occurred an average of 19 days later than under natural conditions.

With the exception of the climatic factor, one should consider that the closure of navigation on the Volgograd-Astrakhan' stretch of river today, resulting from the warming effect of the Volgograd reservoir, occurs an average of 9 - 12 days later than under natural conditions, and an average of 1 - 3 days later on the delta than under natural conditions.

THE ICE REGIME OF THE SOVIET STRETCH OF THE DANUBE, CHARACTERISTICS OF ICE
FORMATION, AND THE POSSIBILITY OF COMPILING SHORT-TERM FORECASTS

By: A. V. Shcherbak, L. I. Solopenko

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The Danube River, flowing through the territory of eight nations in central
and southeastern Europe, has important significance as a transportation main and
as a source of hydroelectric power and land irrigation.

The work of T. N. Makarevich and Z. A. Yefimova (5) has been devoted to
analyzing and summarizing available data on the Autumn-Winter ice regime of the
Danube over the 1900 - 1955 period for the purpose of identifying the possibility
of predicting its characteristics. However, the above authors did not examine
the characteristics of ice formation on the Soviet stretch of the Danube. The
ice regime of the Danube delta has been described in works (1, 3) and in scientific
reports of the Danube GMO.

In 1969 - 1972, investigations were carried out at the Ukrainian NIGMI of
conditions of ice formation on the Soviet stretch of the Danube for the purpose
of developing a method of short-term forecasts of the beginning of separate phases
of the ice regime and the degree of blockage hazard (2, 6, 8 - 10). The investi-
gations were carried out on the basis of data obtained from hydrometeorological
observations over the 1945 - 1970 period, for which data are available on air and
water temperature. Data on ice phenomena from 1931 through 1944, taken from a
study (3), were additionally used to obtain quantitative characteristics of the
ice regime.

The investigated stretch of the river is located in the extreme southwestern
part of the European territory of the USSR, which is characterized by an unstable
temperature regime in the Autumn and Winter. The unique nature of the ice regime
on this stretch of the river is also associated with this factor: the first
appearance of the ice can be observed here from the middle of December to the
beginning of February, although the ice formations are occasionally entirely
absent. Thus, over a period ranging from 1931 through 1970 stable ice phenomena
in the lower reaches of the Danube existed in 22 of the 39 years, which comprises
56% of the time. In ten years (or 26% of the time), ice phenomena were either
absent or were extremely brief (up to 3 days). In the remaining years, periods
with unstable ice phenomena were observed when ice formation was interrupted and
renewed over the course of the Winter 2 or 3 times. The total probability of the
appearance of ice on the investigated stretch of the Danube comprises 82% and the
establishment of icing totals 54%.

As on the entire lower Danube (5), the amplitude of dates of the appearance
of ice and establishment of an ice cover is very large - it reaches 54 to 58 days.
On the Soviet stretch of the Danube the ice appears almost simultaneously over
its entire extent. The earliest appearance of ice was noted on the stretch on
12 - 13/XII (1945), and the latest was observed on 7 - 8/II (1965). The average
date of ice appearance is 4 - 5/I.

The stationary ice cover on the lower reaches of the Danube is established because of the formation of ice necks and the freezing of floes coming downstream. The early establishment of ice on the Soviet stretch of the Danube was noted on 17 - 20/XII (1948), the late one on 9 - 11/II (1956), while the average dates are 12 - 14/I. The average duration of the period with ice is 20 days, ranging from 2 to 79 days in separate years.

Depending on the times of onset of the ice-forming processes, four groups of years have been identified on the Soviet stretch of the Danube:

1. Years of early ice appearance - the onset of ice phenomena was observed no later than 25/XII (1945 - 46, 1946 - 47, 1948 - 49, 1953 - 54, 1961 - 62, 1962 - 63, 1969 - 70).

2. Years in which the first appearance of ice was noted on dates similar to the average multiannual ones, i.e., from 26/XII through 19/I (1944 - 45, 1949 - - 50, 1956 - 57, 1963 - 64, 1965 - 66, 1967 - 68, 1968 - 69).

3. Years of a late (after 19/I) onset of ice phenomena (1950 - 51, 1955 - - 56, 1959 - 60, 1960 - 61, 1964 - 65).

4. Years when the ice phenomena were absent or short-lived (up to 3 days) (1947 - 48, 1951 - 52, 1952 - 53, 1954 - 55, 1957 - 58, 1958 - 59).

Under conditions of mild winters with frequent warming spells, when the sum of negative air temperatures over the period of icing basically comprises 80 - - 130°, the average thickness of the ice on the stretch of Soviet Danube does not exceed 25 - 30 cm and can reach 50 - 70 cm only during rare, severe winters.

Despite such instability of the ice regime, the development of ice formation on the Soviet stretch of Danube in the Autumn and Winter and the debacle in the Winter - Spring are frequently accompanied by ice barrier and ice dam phenomena. The thick barriers and ice dams occasionally cause catastrophic elevations in water level. Multiannual observations of ice phenomena on the Soviet stretch of the Danube show that the formation of ice barriers and ice dams usually occurs on the same stretches of the river (1 - 3), where the water surface slope sharply drops and one notes sharp bends, channel constrictions, islands and shallow bar stretches of delta rivulats.

Small ice barriers and ice dams usually form during the Autumn - Winter ice gang. Their thickness chiefly depends upon the water level of the river and the intensity of cooling, i.e., on factors that determine the intensity of ice formation. The Autumn barrier-dam phenomena can be subdivided into two groups depending upon this factor:

1) those that form during sharp cooling and a high water level of the river at the beginning of ice formation;

2) those formed by sharp fluctuations in air temperature over the course of a long period of ice formation.

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Ice dams achieve extensive development on the Soviet stretch of the Danube in the period of debacle and the Spring debacle. Particularly thick ice jams were observed in the Spring of 1954, 1967, and 1969. The formation of Spring ice jams is determined to a significant extent by the severity of the Winter, the nature of establishment of icing in the previous Autumn-Winter period, the intensity of development of the Spring processes and the condition of the ice on the river shoreline.

Depending upon the degree of influence of some particular factor, one can isolate two types of ice jams:

1. Jams that form as the result of mechanical destruction of a firm ice cover by a water wave; these appear after severe winters, when a significantly thick ice cover forms on the lower reaches of the Danube. If the ice cover proves to be mildly broken up by the thermal factors by the time of debacle, then during debacle large ice fields of firm ice wedge in between the banks, creating favorable conditions for vast accumulations of ice which continuously come in from upstream.

2. The ice jams which are due to the character of establishment of the ice cover in the previous Autumn-Winter period. These form in years when thermal factors predominate in destruction of the ice cover. Ice jams or ice dams are usually observed on river stretches where the thickness of the ice in the Autumn-Winter period is 30 - 40% greater than on the upper and lower stretches of the river. Therefore, the Spring debacle is retarded in this spot and the ice coming down from upstream, in piling up on the edge of the ice, blocks the flowing section of the river channel.

In addition to the indicated types of ice jams, combination types of ice jams can exist on the investigated stretch of the Danube, when their formation is facilitated by sea ice which closes the mouth of delta rivulets during driving winds, as was observed in 1967, and particularly in the Spring of 1969.

Investigations of the synoptic processes which determine weather conditions and cause ice formation and debacle acquire important significance during the analysis of the developmental course of individual ice regime phenomena, particularly when they are highly unstable.

An analysis of atmospheric processes (6), showed that significant cooling in the examined region occurs when the branches of anticyclones formed in masses of Arctic or cooled continental polar air move in from the north, the northwest or the northeast. However, in order to identify the conditions of formation of the indicated local synoptic processes one must refer to the investigation of the characteristics of total atmospheric circulation in the Autumn-Winter period which cause their appearance.

For this purpose, the classification of macroprocesses according to circulation indices, suggested by A. L. Kats (4) was used. It was established that cooling in the examined region is most often due to meridional processes with the circulation forms Ts, Z, and C, and that cooling very rarely occurs during atmospheric processes due to the easterly position of the ridge, i.e., circulation of form B. This made it possible to assume that the totality of cir-

culation processes of the indicated forms is also a combination of macroprocesses under whose influence the weather conditions form which determine any of the particular dates of ice appearance on the investigated stretch of the river (6). The multiple of the number of days with circulation form B and of the total number of days with circulation of the other forms over the course of a certain period is accepted as the indicator of this combination N. This indicator, determined according to the indices of atmospheric circulation, is calculated according to the following formula:

$$N = n^B_{<22>+<11>+<21>+<12>} - \left(n^3_{<22>+<11>+<21>} + n^{Ts+C}_{<22>} \right)$$

in accordance with the method presented in Kats's work (4).

The annual course of monthly values of the index N averaged for the groups of years calculated according to the dates of ice appearance shows that the greatest differences in the course of the curves for different groups observed in August - October. In the course of this period, each group of years has its own inherent character of formation of the synoptic processes from month to month.

The course of index N in time in individual years does not fully duplicate the course of its average values. However, the signs referred to above are maintained for years of the early and late ice formation by values, respectively, of 89 and 80%, while for years with normal dates of appearance of the ice phenomena and years of no ice phenomena, the magnitude of conformance is 70%. Consequently, on the basis of the signs already identified at the end of October, one can state with a probability indicated above whether the ice formation in the current season will be early, late, near the normal date, or unanticipated altogether.

The estimate of the forecast conclusions based on the material of 1969 - 1970 and 1970 - 1971, which did not enter into the selection, demonstrated that they could be utilized to compile approximate forecasts of the onset of ice formation on the Soviet stretch of the Danube River. The development of a method of short-term forecasts of the beginning of ice formation is necessary to refine these qualitative predictions.

Today, such forecasts are compiled according to empirical relationships or by means of calculation. The construction of the empirical associations is based on establishing local relationships of the dates of appearance of ice with certain factors. The latter include the total of negative air temperatures necessary for the appearance of ice, the temperature of the water and the water level of the river by the time air temperature crosses $0°C$.

The indicated empirical relationship for establishing the time of appearance of ice on the Danube River near the city of Izmail, cited in a work (8), can be represented in the following form:

$$(\Sigma\theta-)_{min} = A\vartheta^{1.29},$$

where $(\Sigma\theta-)_{min}$ is the total of negative average daily air temperatures needed for the onset of ice formation; ϑ is water temperature near Izmail Chatal immediately before air temperature crosses $0°C$. The value of parameter A is determined depending

upon the flow rates of water: when $Q > 4500$ m^3/sec, $A = 10.5$; when $Q = 4500 - 3500$ m^3/sec, $A = 7.2$, and when $Q < 3500$ m^3/sec, $A = 4.9$.

Calculation of the dates of appearance of ice made with the use of this relationship yields fully satisfactory results: the errors of the verified forecasts for the 1946 - 1967 period do not exceed 2 days in 94% of the cases.

Applicable to the conditions of the extreme southwestern part of the European territory of the USSR (taking into account features of the examined stretch of the Danube River associated with the presence of an extensive delta), a calculation was made of the time of ice appearance according to the method of L. G. Shulyakovskiy (7). The results of calculations of the times of ice appearance near the city of Izmail showed that on 19 of the 23 calculations for dates that were carried out (83%), the error was zero. The frequency of error was no more than 1 day, comprising 87%, while an error frequency of no more than 2 days comprised 97% (9).

It is known that the characteristic of Winter severity, and consequently, the indicator of development of the ice-forming processes can be the anomaly of air temperature in Winter. Comparing these anomalies in the southwestern part of the European territory of the USSR ($\overline{\Delta T}_{XII-II}$) and the average duration of ice cover on the Soviet stretch of the Danube showed that a quite intimate relationship exists between the indicated characteristics. In seasons with $\overline{\Delta T}_{XII-II} \geqslant 1^o$, in 93% of the cases the ice cover in the lower reaches of the Danube was practically absent, and when there was a negative anomaly ($\overline{\Delta T}_{XII-II} < -1^o$), in 86% of the cases one noted an ice cover lasting over 20 days. In cases when $-1^o < \overline{\Delta T}_{XII-II} < +1^o$, the air temperature anomaly in Winter was not intensive enough to be a reliable characteristic of the anticipated duration of the ice cover; the latter in such years is determined by the distribution dynamic (alternation dynamic) of cold and warm waves during Winter and by the effect of a number of other factors, for example the water level of the river.

In this investigation, the authors attempted to estimate the hypothetical severity of Winter by using the magnitude of the average air anomaly. In analyzing the course of the indicator of the combination of macroprocesses N, the authors succeeded in identifying contrasting periods, whose process differential indicators could serve as the forecast signs of the average air temperature anomaly sign in Winter in the southwestern part of the USSR. The basic forecasting sign of the investigated phenomenon was the transformation of circulation in the troposphere from August to September: when there was a positive difference in the macroprocess indicators from August to September ($N_{XIII} N_{IX} > 0$, one should anticipate a cold Winter or a Winter near the norm - $\overline{\Delta T}_{XII-II} < 0$ (frequency 92%); when $N_{VIII} - N_{IX} < 0$, one should anticipate a warm Winter at least in the southwestern part of the European territory of the USSR - $\overline{\Delta T}_{XII-II} > 0$ (frequency 86%).

Analysis of the hydrometeorological and synoptic conditions of ice jam formation was made for the purpose of determining the degree of ice jamming and to identify the possibility of comparing the warnings of the appearance of dangerous ice jams and ice dams in the low water reaches of the Danube. Over

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the 1945 - 1970 period, there were no more than 5 - 6 such jam-dam phenomena on individual stretches of the river. With such a limited assortment of original data, one can only discuss the approximate estimate of the degree of ice jam hazard and the probability of the formation of dangerous ice jam-ice dam phenomena.

It was established that the following are the criteria of ice jam hazard which make it possible to issue warnings about the probable formation of dangerous ice jam-ice dam phenomena on the Soviet stretch of the Danube:

a) severe (up to -15° and below) cooling at the beginning of ice formation with a high water level (the water level no lower than 200 cm at the Ren' water monitoring station);

b) ice thickness on the stretch in excess of 40 cm at the time of debacle;

c) cases when the direct establishment of ice cover in the Autumn and Winter was preceded by ice jam-ice dam phenomena;

d) the presence of stable northeasterly or easterly winds during the ice gang period and the presence of adhesive or floating ice in the western part of the Black Sea.

The obtained conclusions have satisfactory accuracy for use in working practice, despite the fact that some of them are approximate and rough. Their further refinement and improvement are possible proportional to the accumulation of original data based on analyzing the entire combination of hydrometeorological and synoptic conditions which determine the developmental character of ice-forming processes on the Soviet stretch of the Danube.

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CALCULATIONS AND FORECASTS OF THE AUTUMN ICE FORMATION ON RIVERS, LAKES, AND
RESERVOIRS OF KAZAKHSTAN

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The thermal and ice regimes of rivers, lakes, and reservoirs of Kazakhstan
are extremely varied. One can identify the following groups of rivers and their
stretches according to the Winter regime:

   I - rivers with a stable ice cover;

   II - rivers with a predominantly unstable and intermittent ice cover;

   III - rivers with ice phenomena but without a continuous ice cover or with
an ice cover only during particularly severe winters;

   IV - river stretches without ice phenomena.

All of these groups of rivers are encountered in the southeastern regions of
the Kazakh SSR; over the greater part of Kazakhstan, one has rivers with a stable
ice cover and they frequently freeze to the bottom even in open stretches. An
exceptionally low water content is a feature of many of the Kazakhstan rivers.
Some rivers in the northern and middle regions of the republic dry-up in the
Summer and Autumn and represent a system of disparate stretches of water which
freeze in a fashion similar to small lakes.

The aqueous mass of the large rivers cools more slowly than that of the
small ones. This retards the appearance of ice on large rivers by an average
of 3 - 7 days. The Autumn ice gang is only observed on the large rivers (Irtysh,
Ural, Syrdar'ya and the Ili; it is less frequently observed on the Karatal, the
Lepsy and others). It is usually accompanied by the formation of large ice piles
on the shores. Most often the Autumn ice gang is associated with the break-
through of ice jams and ice dams. Sub-surface ice whose formation is the most
characteristic feature of mountain rivers in Winter plays the primary role in
the ice regime of the mountain rivers. The amount of brash ice transported by
some rivers reaches a high value, particularly on the Irtysh, the Syrdar'ya and
the Ili.

Ice dam phenomena are frequently observed on mountain streams. These in-
flict great losses on inland waterway management and hydrotechnical facilities.
Brash ice-ice conglomerations are frequently observed during the break-through
of ice dams.

The formation process of the ice cover on Kazakhstan rivers takes up a long
period (on the average, from the III decade of October to the I decade of December
up to the II decade of November to the II decade of January). A number of rivers
in the southern regions of the republic does not freeze every year. The esta-
blishment of an ice cover along the length of a river depends on the flow
direction.

In the first half of the Winter one observes an intensive build-up of the ice cover and already in the first half of December the rapids on many plain rivers freeze down to the bottom. By the end of December the average ice thickness is 15 - 75 cm and the maximum ice thickness is 40 - 95 cm. The highest values (up to 40 - 220 cm) of ice thickness are reached at the end of February - March. In individual years, because of thick accumulations of sub-surface ice and the formation of ice piles, the thickness of the ice can reach 4 - 5 m (4). The ice piles are responsible for the stratified character of the ice cover. The ice cover on Kazakhstan rivers averages a duration ranging from 35 to 175 days (the longest duration runs from 95 to 195 days).

The beginning of debacle generally falls to the I decade of January - the middle of April (the latest dates of river clearance from ice range from the III decade of February to the I decade of May). In connection with the increase in solar radiation, the ice cover on the Kazakhstan rivers begins to break-up still before the onset of stable positive air temperatures. The river debacle occurs under the effect of both thermal and mechanical factors.

The average duration of the period with ice phenomena on rivers with a stable ice cover is 105 - 190 days (the shortest is 45 - 175 days and the longest is 140 - 215 days). In the southern regions of the republic, the length of the period with ice phenomena are significantly shorter (up to 70 - 150 days). The debacle and clearance of rivers from ice is somewhat less extended in time than their freezing process.

The ice regime of the rivers changes sharply when the flow is regulated. The process of ice cover formation and its destruction on many reservoirs in Kazakhstan are similar to the analogous processes that occur on rivers under natural conditions. On comparatively large reservoirs, the ice cover is established earlier.and more rapidly on stretches where the abutment wedges out into the stream and somewhat later (by 20 - 35 days) directly adjacent to dams (4), where open stretches of water frequently do not freeze over the entire Winter. Investigations conducted on the Kengirsk, Ust'-Kamenogorsk and Bukhtarminsk reservoirs demonstrated that under the conditions of Kazakhstan the change in the dates of onset of ice formation and the establishment of the continuous ice cover on regulated rivers can be calculated with sufficient accuracy according to the method of L. G. Shulyakovkiy (7, 8), using the formulas of A. P. Braslavskiy and Z. A. Vikulina (1954) for calculating the thermal balance components.

The construction of the Kapchagaysk hydroelectric power plant on the Ili River and the reservoir, which is a combination water management object, is solving problems of the development of energy generation, agriculture and fish management, was completed in the Ninth Five-Year Plan. The operation of the Kapchagaysk hydroelctric power plant strongly depends on the ice regime of the reservoir. The functioning of a number of economic organizations which capitalize on the water riches of the reservoir, the development of inland waterway transport, and other branches of the national economy also depend upon the ice situation.

In order to service the management organizations in Winter, the authors

began to study the ice regime of the Kapchagaysk reservoir in addition to investigating the ice regimes of existing Kazakhstan reservoirs. Formulas were chosen for the thermal balance calculations (5), and a method of forecasting the dates of onset of different phases of the ice phenomena was developed.

The basis of calculating ice formation on reservoirs in Kazakhstan was the following inequality

$$t_n \leqslant -\frac{B_n}{\alpha_n},$$
(1)

where t_n is the average water temperature according to depth at the end of the n-th interval of time; $\frac{B_n}{\alpha_n}$ - the depth-average water temperature at the time of beginning of ice formation, i.e., the temperature at which the beginning of ice formation is possible under the given meteorological conditions; B_n is the specific heat yield of the water surface at the time of beginning of ice formation; α_n is the coefficient of heat yield from the water mass to the surface of the water-air interface at the time ice formation begins. The calculations were made with the aid of nomograms plotted for the conditions of Kazakhstan.

The inequality (1) was verified on the basis of full-scale data for Lake Balkhash, the Kengirsk, Ust'-Kamenogorsk and Bukhtarminsk reservoirs, as well as the Ili River along the free course, taking into account the annual and averaged hydrological data, since for the Kapchagaysk reservoir one cannot take into account hydrological data for past years (the reservoir did not exist). In 77% of the cases, the error of calculation for the Ili River over a 35-year period in the region where the reservoir was built is ± 1 day and comprised 77%. It was 83% for ± 2 days and 94% for ± 3 days. The maximum calculation error was 6 days (1956). In the Winter of 1940 - 1941, there was no ice cover. This was in fact obtained as the result of calculation. The preliminary calculations made it possible to represent the anticipated process of Autumn ice formation on the Kapchagaysk reservoir. Freezing of reservoir stretches with an average depth of 3 m and a current velocity of 0.1 m/sec is anticipated one day earlier, on the average, than on the Ili River with a free flow. The average date of freezing of these stretches is 13/XII according to the calculation and the earliest date is 23/XI, while the latest is 18/I. The appearance of floating ice is anticipated on 5/XII, on the average, according to the calculations. This is 8 days before reservoir freezing (the extreme dates of floating ice appearance are 18/XI, 1972, and 3/I, 1942).

These same stretches (3 m deep) with a flow velocity of 0.2 - 0.3 m/sec on the average, should freeze one day later than the Ili River in this region with free flow, according to the calculation. The extreme dates fluctuate from 23/XI through 19/I. The appearance of floating ice (without taking into account transit brash ice) is also anticipated an average of 7 - 8 days before the formation of the continuous ice cover. In separate years this period can also extend for more than a month (1939).

The freezing of stretches of the Kapchagaysk reservoir with an average depth of 5 m, according to the calculation, is expected 7 - 9 days later than that of the Ili River to the point of its regulated flow. The extreme dates

fluctuate from 27 - 29/XI through 16 - 23/I. The appearance of floating ice is expected 3 - 6 days earlier, on the average.

Stretches of the reservoir with an average depth of 7 m are expected to freeze, on the average, 11 - 13 days later than the Ili River under natural conditions, according to the calculation. On stretches of the reservoir with an average depth of 5 m or more, large stretches of open water should be observed in individual Winters. Thus, in the Winter of 1939 - 1940 the ice cover was absent, according to the calculation, on stretches of river whose average depth is 5 - 7 m. It is anticipated that the ice regime of the Ili River in the lower reach of the Kapchagaysk reservoir will be unstable. Here favorable conditions are created for the accumulation of brash ice and the formation of ice dams.

According to the calculation, the formation of a continuous ice cover through the Kapchagaysk reservoir aquatorium will occupy a long period of time. It will reach an average of over 16 days (from 4 to 57 days) for stretches whose depth ranges from 3 to 7 m alone. 8 - 10 days after stretches of the reservoir 3 m deep have frozen, one anticipates freezing of stretches with an average depth of 5 m, then, in 12 - 14 days, freezing of stretches whose depth is 7 m. Deeper stretches of the reservoir should freeze significantly later.

Sharp periods of nocturnal cooling can cause the metal components of the hydrotechnical facilities immersed in the water to freeze (gratings, shields, spillway structures, etc.). This can occur prior to the appearance of particles of floating brash ice on the water surface.

Freezing maps have been drawn for the large Kazakhstan reservoirs (Lake Balkhash and the Bukhtarminsk reservoir) according to the meteorological data. These maps enable agencies of the hydrometeorological service to provide service to fishing industry regions which are remote from the water monitoring stations (3). The inequality (1) also forms the basis of the calculation. In order to test the calculations of freezing dates of different little-studied reservoirs in Kazakhstan, the materials of ice aviation surveys were used. These are generally in good agreement with the maps drawn according to the calculation data (1).
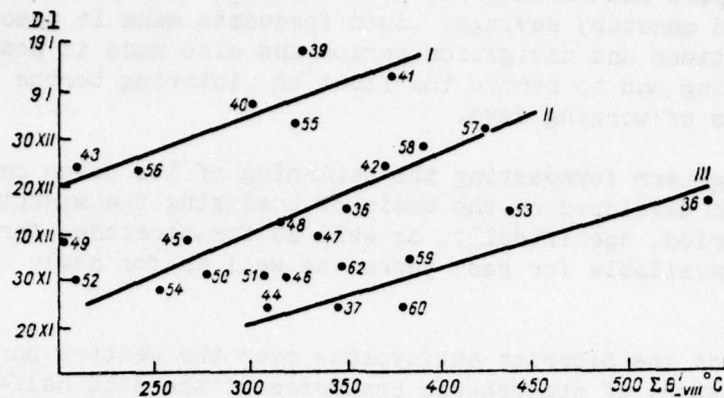
The generalized multiannual maps of the average, early, and late reservoir freezings provide a complete characterization of the regime of Autumn ice formation. Thus, the formation of the continuous ice cover for the Lake Balkhash aquatorium according to maps drawn on the basis of calculation data, occurs on the average in 36 days (from 16 to 67 days). On the average, stretches of the lake about 10 m deep freeze 7 - 8 days after stretches 4 - 6 m deep freeze. Stretches about 15 m deep freeze 15 days after the latter and those about 20 m deep freeze about 20 days later. The Zaysansk stretch of the Bukhtarminsk reservoir freezes much quicker. Comparing the freezing maps drawn according to the data of ice aviation surveys and the meteorological data showed that one can forecast the reservoir freezing dates in any part of the reservoir with a timeliness factor of 3 - 5 days, using the weather forecasts. The working short-term forecasts of freezing of separate regions of Lake Balkhash for

servicing the transport and fishing fleet in the hazardous period of ice formation produced a good monetary savings. Such forecasts made it possible to increase the fishing times and navigation period and also made it possible timely to prepare for fishing and to remove the fleet to wintering berths in timely fashion without loss of working days.

Methods of long-term forecasting the beginning of ice cover on Kazakhstan reservoirs have been developed on the basis of analyzing the synoptic processes of the preceding period, specifically, as well as for stretches for which hydrological data are unavailable for past years, as well as for newly created reservoirs (2).

The formation of the Siberian anticyclone over the western horn of Kazakhstan is a significant feature of atmospheric processes of the cold half-year. The Siberian anticyclone is frequently a continuous strip of high pressure which intersects the examined territory along its medial latitudinal zone and has a significant effect on climate and weather. Its extent and break-up determine the nature of the Autumn and Spring ice phenomena. The movement of anticylcones along meridional trajectories is also very significant for the circulation processes and climate of Kazakhstan. Analysis has shown that the intensive formation of ice in rivers and reservoirs here most frequently occurs with predominance of the eastern type of atmospheric circulation, according to G. Ya. Vangengeym. The predominance of the meridional type of circulation, as a rule, causes later ice formation at the end of November and in December in the central regions of Kazakhstan and at the end of December and in January in the southern regions. The ice debacle is most often observed when the cyclones extend from the southwest. The earliest dates of river debacle in the southern regions of Kazakhstan are due to the southwesterly movement of air masses in February in the absence of northwesterly incursions, and in March for the rivers in Central Kazakhstan. The late dates of debacle are observed when there are northern and northwesterly incursions of anticyclones in March and April.

The inverse relationship which exists between processes in September and November, identified by the authors and other investigators, is a feature of the synoptic processes that exist above the examined territory. Different characteristics of atmospheric processes used for long-term forecasting of ice phenomena have been identified by analyzing the synoptic conditions which cause ice formation on rivers, lakes, and reservoirs in Kazakhstan. According to the authors' investigations, an inverse relationship exists between the temperature of the air during warm half of the year and the onset of icing. Thus, reservoirs in the southeastern part of Kazakhstan usually freeze earlier with a comparatively high air temperature in August and September, while later ice formation frequently exists during predominance of low temperature at this time. A comparatively close association has been identified between the calculated dates of freezing of the newly built Kapchagaysk reservoir and the total of average daily air temperatures in August $\Sigma\Theta_{-VIII}$, which are less than the average decade multiannual ones for this month (see the figure). In the figure, one clearly traces three directions of points due to the different types of synoptic situations (meridional C, westerly W and easterly, E types of circulation). The forecast relationships which exist between the sum $\Sigma\Theta_{-VIII}$, characterizes cooling in August and is due to the various atmospheric processes, and the beginning of ice formation and have been identified for Lake Balkhash.

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191
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30 XII
20 XII
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30 XI
20 XI

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•56 42•
•36 •53 III
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•54 •50 51• •46 •62
44• •37 •60

250   300   350   400   450   500 Σ θ'ᵥₘ °C

The relationship between the beginning of icing on the Kapchagaysk reservoir (h = 3 m, u = 0.1 m/sec) and the total of low air temperatures in August during varying synoptic situations in the previous Winter.
I - predominance of the meridional type of circulation; II - predominance of the westerly type of circulation; III - predominance of the easterly type of circulation.

The forecast relationships which exist between the indices of atmospheric circulation on 1 September, calculated according to maps of barometric topography AT_{500} and freezing of Lake Balkhash (1) yield good results. This index characterizes both the meridional airstreams in the troposphere and, to a certain extent, the latitudinal ones.

The development of methods of forecasting the beginning, development, and end of ice phenomena with a high timeliness factor under the conditions of Kazakhstan is a complicated problem. A number of the developed methods for long-term forecasting of the onset of icing in southeastern Kazakhstan is used in the practical work of the UGMS, KazSSSR and has been since 1960. Experience gained in compiling the long-term ice phenomena forecasts for Lake Balkhash with a timeliness factor of 1.5 - 2 months have yielded positive results for this period (6).

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CALCULATIONS AND FORECASTS OF FREEZING DATES AND ICE CLEARANCE DATES OF THE VOLGA RIVER RESERVOIRS

(A Method and Experience in Practical Support of the Inland Waterway Fleet)

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Moscow)

The grandiose hydrotechnical construction which has unfolded since the beginning of the 1950's on the large rivers in the USSR has faced forecast hydrologists with the necessity of issuing forecasts for new objects that have still unknown ice regimes.

As the result of investigations conducted at the Hydrometeorological Center of the USSR, L. G. Shulyakovskiy, V. V. Piotrovich and S. N. Bulatov (3, 8, 9) have obtained methods which enable one to calculate the annual dates of freezing of reservoirs and their ice clearance in the absence of observation data. With the aid of these methods, meteorological data for past years and the hydraulic and morphometric characteristics of reservoirs are used to calculate the annual dates of freezing and ice clearance of practically all newly created reservoirs as provided by the project. This primarily includes the Volga River reservoirs, which are used to provide for a significant fraction of the cargo turnover of the inland waterway fleet of the USSR. Calculations of the multiannual series were carried out for the Gor'kiy, Kuybyshev, Saratov and Volgograd reservoirs (2, 6). Moreover, the curves of frequency of the dates of ice phenomena were calculated for the Cheboksarsk hydroelectric power plant reservoir, which is under construction (7).

The obtained multiannual series encompassed various conditions, including the extreme ones. The series make it possible to obtain the regime characteristics of freezing and clearance of reservoirs according to a probability form, to identify changes in the ice regime in comparison with the river under natural conditions, and to determine the effect of the morphometric and hydraulic factors on these changes. Furthermore, these series served as the regime basis for developing methods of long-term forecasts.

A forecast was prepared by carrying out the indicated operations by the time of startup of each reservoir (the forecast was the probability characteristic). This forecast dealt with the ice regime, and beginning with the first year of existence of the reservoir long-term and short-term forecasts of freezing and ice clearance were regularly issued.

Now, when certain data of full-scale observations made on reservoirs have been accumulated, one can attempt to test our assumptions about the change in the dates of ice phenomena resulting from regulation. The largest series of observations is available for the Gor'kiy, Kuybyshev (17 years) and the Volgograd (14 years) reservoirs. The dates of ice phenomena observed on the reservoirs were plotted by the authors on appropriate frequency curves which were in turn plotted according to the series calculated earlier. Certainly, such a comparison

is not very valid since one is comparing series of different length, and more-
over, when climatic characteristics of a period can influence the accuracy of
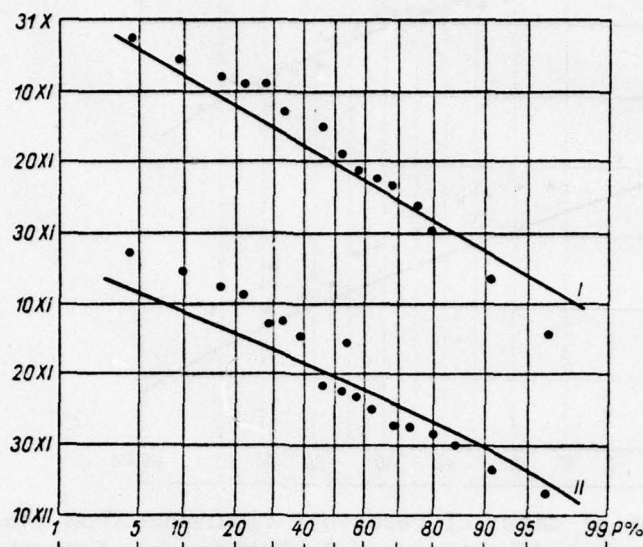the comparison if the series is short.

Figure 1. A comparison of the freezing dates of reservoirs with the frequency
curve obtained according to the calculation.
1 - Kuybyshev reservoir, upper slope; II - Gor'kiy reservoir, Kostroma-Yur'yevets
stretch.

The freezing dates of the limiting stretches of the Gor'kiy and Kuybyshev
reservoirs over the 1956 - 1972 period are superimposed quite satisfactorily
(Figure 1) on the frequency curves of the calculated dates for 1925 - 1955.
One can only note a slight tendency toward deviation of the actual dates to
the early side, which is evidently explained by predominance of the lowered
water level background on the Volga River at that time. The changeability of
dates on the Gor'kiy reservoir over the years of its existence was somewhat
greater than according to the calculation. The calculated changeability is
probably too low, inasmuch as the annual fluctuations in flow rate in the intake
stretch were not taken into account.

. The ice clearance dates of the Kuybyshev reservoir lie precisely on the
frequency curve obtained from the calculation series (Figure 2). The observed
dates of clearance of the Gor'kiy reservoir are also near the curve. The
greatest deviations here are noted in the late dates, with a frequency of more
than 80%. Reservoir ice clearances were not observed after 10/V over the years
of existence of the reservoir, while according to the calculation such dates
could appear once every 10 - 15 years. The observed dates of clearance of the
Volgograd reservoir lie noticeably earlier than the calculation curve. Here
one patently has a certain systematic error in the calculation of 3 - 5 days
which evidently appeared as a consequence of failing to consider the flow rate
of the reservoir in the calculations and the influx of heat to the lower surface
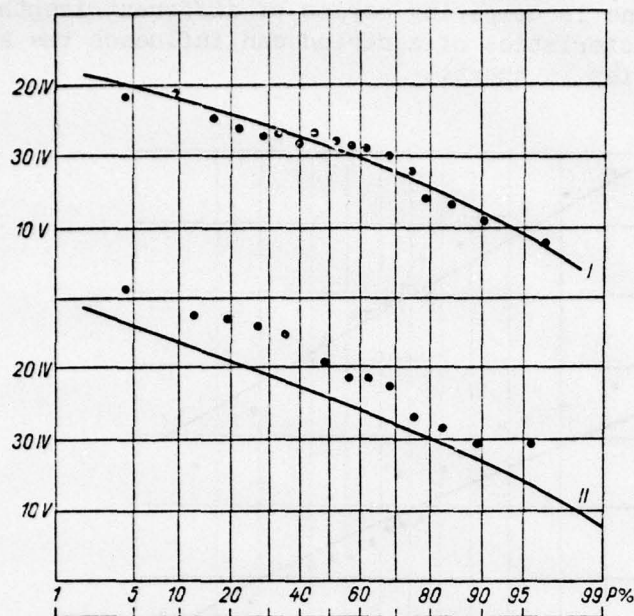of the ice, which can be significant in the southern regions.

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Figure 2. A comparison of dates of reservoir clearance from ice with the frequency curve obtained according to the calculation. 1 - Kuybyshev reservoir, II - Volgograd reservoir.

The probable deviation in the observed dates of ice phenomena from the curve calculated before does not exceed 2 days for all reservoirs with the exception of the Volgograd one.

While reckoning with the insufficient strictness of the cited comparison, we still consider it possible to conclude that the concepts concerning the change in the ice regime of the Volga River obtained according to the calculation data were basically correct.

One can state the following in summarizing the results of the calculations and observations.

The change in the freezing dates of reservoirs in comparison with the river is determined by the change in depths, flow velocities and the position of the reservoir in the hydroelectric power plant cascade. On the Kuybyshev reservoir, above which (on the Volga and Kama stretches) the Volga River is in a relatively natural state, the first ice necks which limit navigation form in the zone of hydroelectric power plant abutment wedging, where a sharp drop in flow velocity occurs and the lowest depths are observed. Ice appears here 3 - 5 days later than on the same stretch of the river under natural conditions, while the ice cover forms 10 - 15 days earlier.

On the Gor'kiy, Saratov, and Volgograd reservoirs, whose upper part is under the effect of the hydroelectric power plant located upstream, the location of the first ice neck shifts slightly below the zone of abutment wedging and annually changes depending upon the magnitude of the flow rates of water through the hydroelectric power plant. The ice appears 6 - 10 days later here than does

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floating ice on the river, and the ice cover begins to form 10 - 12 days later than floating ice appears on the river, and totals 2 - 5 days before the river freezes under natural conditions. The new Cheboksarsk reservoir will be included among the same group of reservoirs (7). Hence, a comparison of the nature of freezing of single reservoirs and those located in the hydroelectric power plant cascade shows the advantage of the latter from the standpoint of the duration of the Autumn navigation period.

Comparing the frequency curves of dates of ice appearance and the onset of the ice cover on the river and on the reservoirs shows that the probability of early ice formation noticeably diminished over all stretches of reservoirs. One also notes a general decrease in changeability of dates of the Autumn ice phenomena proportional to river regulation. On the one hand, the latter is associated with the more rigid freezing at the late dates, and on the other is associated with the greater equalization of the aqueous regime under regulated conditions. The effect of flow rates of water flowing through the reservoir on the onset dates of icing is extremely significant, particularly during unstable weather at the time of freezing. In individual years the increase in the flow rate of water by 30 - 50% can lead to retardation in the onset of icing on the Volga stretch of the Kuybyshev reservoir or in the upper part of the Volgograd reservoir by 8 - 12 days (1, 6). This circumstance can and should be used to extend navigation into the Autumn.

In Spring, the ice cover is preserved longest on the widest stretches of the reservoir and in the stagnant, closed coves. The clearance of these stretches from ice limits the beginning of normal navigation. On the Volgograd reservoir, which is sharply elongated along the meridion, the difference in conditions of the influx of heat has a noticeable effect on the break-up of ice. The lower, southern part of the reservoir clears of ice significantly earlier than the upper part, although its width in the part near the dam is greater but the flow velocity is slower.

The change in the dates on which the reservoirs are clear of ice, in comparison with the dates observed on the same stretches of the river under natural conditions, is chiefly determined by the direction of flow of the river, the duration of the Spring debacle and the flow of the reservoir. Based on the example of the Volga River, this is traced particularly clearly. All reservoirs located on the upper course of the river, where the debacle was brief under natural conditions, free from ice significantly later than the river itself. The difference is most noticeable on the early dates. The dates of clearance of reservoirs with a frequency of 10% are noted 11 - 14 days later than the corresponding dates on the river. For the late dates (dates with a frequency of 90%), this difference shortens to 6 - 8 days and even to 3 days in the Uglichsk reservoir, which has a strong current. In the Kuybyshev reservoir, where the duration of the Spring debacle increased under natural conditions due to the transport of ice from the Kama River, the difference in clearance dates comprises a total of 2 days for the moderate dates.

Prior to regulation, the lower Volga opened from downstream to upstream. Here the consequence of the in-flow of ice from the upper, more northerly stretches of the river was a prolonged ice gang, first of the Volga ice, then the Kama ice; the total duration of the Spring debacle, the maximum one of all

the rivers of the USSR, averaged to 15 days. After regulation of the river at the Saratov and Volgograd reservoirs, only the "local" ice melts. Its rapid destruction is facilitated by the southerly position of the Volgograd reservoir and by the rapid flow of the Saratov reservoir. As a result, the ice now disappears here 1 - 4 days earlier than under natural conditions. As the investigations of B. M. Ginzburg showed (7), on the whole the changes in the duration of the period of absence of ice on the Volga resulting from regulation are favorable for inland waterway transport.

The character of changes in different reservoirs varies. The most favorable changes occurred on the lower Volga. Here navigation can last an average of 17 - 19 days longer than before construction of the Volgograd and Saratov hydroelectric power plants. On the Volga from Rybinsk to Kuybyshev, changes in the duration of the iceless period are slight. It (the iceless period) diminished significantly only on the upper Volga and at Sheksna following filling of the Rybinsk reservoir, respectively by 2 - 3 and 7 days.

The conclusion that the effect of regulating the Volga is favorable with respect to the duration of navigation is the more correct because under the conditions of the reservoirs the extension of navigation into both the Spring and Autumn periods is significantly facilitated. In Autumn, the ships transit stretches of the first cover ice with the aid of icebreakers. This is particularly effective in years with a broken course of freezing, when the cold waves alternate with prolonged periods of warming and the extension of ice phenomena to the deeper stretches of the reservoirs is retarded. In Spring the icebreakers force a navigable channel in the ice long before the complete break-up of the ice.

Presently, investigations of the build-up in the thickness of the ice in the initial period of icing and losses of stability of the ice cover in Spring are underway at the Hydrometeorological Center of the USSR for purposes of identifying the possibility of long-term forecasting of the dates of onset and termination of navigation in the ice (4). The work will continue, but one can already draw certain conclusions.

The investigations and practical experience derived in the inland waterway fleet demonstrate that modern icebreakers comparatively easily cross ice up to 15 - 20 cm thick. It is difficult to determine the dates of onset of this thickness according to data of available full-scale observations and therefore the authors have proceeded along the path of calculating the daily build-up of ice thickness. The calculation was made for a stretch of formation of the first ice neck on the Kuybyshev reservoir (the Verkhnyy Uslon region) on the computer, using the method of Shulyakovskiy. As the result, a multiannual series was obtained (since 1940) of the dates when the ice thickness reached 10, 15, and 20 cm.

On the average, the ice reaches a thickness of 10 cm on the fourth day of icing, 15 cm on the eighth day; the thickness of ice measuring 20 cm is observed in 15 days. In cases of particularly severe cold, the ice thickness reached 20 cm in only 4 - 6 days, but during an extended Autumn this period can even extend to 30 - 40 days.

The frequency curves of the dates when a certain thickness of the ice is reached run in parallel with the curve of dates of the icing and deviate only in the late cases. A build-up of ice to a thickness of 20 cm is observed in a period from the middle of November to the end of December, on the average to 7/XII. Analysis of the probability of ice build-up showed that one can plan navigation in the ice until the end of November.

A system of methods was developed for operational support of opening and closing navigation on the Volga reservoirs. With the aid of this system (methods), long-term forecasts of freezing and clearance of the reservoirs are issued with a timeliness factor of 1.5 - 2 months and is then refined by forecasts with a lower timeliness rating (10 - 20 days) and by short-term forecasts (over 3 - 5 days).

The long-term forecast methods (5, 6) are based on the use of the relationship of ice phenomena dates with the development of atmospheric processes in the preceding period. The quantitative indicators of the condition and tendency of seasonal restructurings of temperature fields and their pressure fields are taken into account, as well as the characteristics of the flow rate of water running through the reservoir and the ice thickness.

The long-term forecasts are issued in a probabilistic form which makes it possible realistically to estimate the degree of industrial risk in resolving specific management problems. Unfortunately, the probabilistic form of forecasts has still not found extensive application in planning the operation of inland waterway transport.

The general justification of the long-term forecasts over the time of existence of the Volga reservoirs has been 76%. The forecasts of reservoir clearance from ice and forecasts of the early and nearly normal beginning of the icing have been most successfully justified. The forecasts of late freezing are clearly justified: the ice cover formed much later than the anticipated dates. The latter is due to the fact that during development of the method and issuance of the forecasts the technicians involved strove to avoid the most hazardous error for inland waterway transport - unanticipated early freezing. Such errors, and consequently, the associated disruption of accomplishing the plans of transport, accidents and material losses did not occur on the Volga reservoirs. The long-term forecasts and their verifications made it possible nearly always fully to utilize the navigation period. Long-term forecasts of reservoir freezing were particularly effective in recent years, when the method (for the first time in the practice of long-term ice forecasts) made it possible to foresee the disparate, intermittent character of ice formation. Taking these forecasts into account, the intensive operation of the inland waterway fleet, particularly the self-propelled vessels, continued 15 - 20 days after the formation of the first ice necks in 1969 - 1972. The additional time could not be successfully used to the fullest extent for navigation only in cases of a predicted, very late freezing (1962, 1967, 1969), when navigation terminated before the beginning of icing despite the issuance of verifications of the long-term forecasts, since during planning carried out according to the long-term forecast neither the dispatch of cargoes nor the maintenance of the waterway had been planned much later than the dates.

The short-term forecasts, upon which operating decisions concerning opening and terminating navigation are based, are compiled on the basis of calculation methods with the use of forecasts of air temperature and, sometimes, wind and overcast. The timeliness of the Autumn forecasts averages 4 days and that of the Spring ones is 6 days. The high accuracy of calculations (for the Kuybyshev and Volgograd reservoirs, for example, the errors of calculating the beginning of icing did not ever exceed 1 day) ensures adequate reliability of short-term forecasts despite the error of weather forecasts. In 93% of the cases their errors did not exceed the accepted permissible ones.

The immediate prospective for significantly improving the effectiveness of ice phenomena forecasts on Volga River reservoirs is seen in devising methods of forecasting navigation conditions in the ice. The first steps in this direction have already been taken. These are the short-term forecasts of ice build-up issued in 1971 and 1972. These were noticeably useful. Presently, methods of forecasting dates when the thickness and strength of the ice render the movement of ships through the reservoir possible are under development.

An important condition of the successfulness of hydrological support for inland waterway transport is the constant contact of operational agencies of the forecast service with management of the inland waterway fleet. The close cooperation of the Hydrometeorological Center of the USSR with the operating directorates of MRF, RSFSR, the Gor'kiy Weather Bureau with VORP and the Volga BUP, the Kuybyshev Weather Bureau with the "Volgotanker" shipping line, established in recent years, has improved the effectiveness of service, and in many cases has made it possible to make correct operating decisions in a complicated and unfavorable situation. Such decisions have ensured the successful accomplishment of improtant economic tasks.

We consider it expedient to extend cooperation in carrying out investigations aimed at identifying methods of optimum planning of fleet operations jointly with the scientific institutions of MRF, taking into account the probabilistic character of ice phenomena forecasts. Conducting such investigations, in addition to improving methods of forecasting ice phenomena and developing methods of forecasting the conditions of ice navigation, will make it possible to improve the support of inland waterway transport, one hopes, by providing ice forecasts at a new, higher level.

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FORECASTS OF MAXIMUM ICE JAM WATER LEVELS IN LOCATIONS WITH ANNUAL ICE JAM FORMATION

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Ice jams have been studied very little. Only the qualitative features of the process are more or less known. The quantitative evaluation, and specifically calculating and forecasting the maximum ice jam level, is possible in a few cases. Such a state of this problem is due to many objective factors: the complexity of the process, the high cost and laboriousness of field observations, and finally, the impossibility of accurately duplicating the phenomenon under laboratory conditions. Subjective factors also play a certain role. Until recently, investigations of ice jams were dominated by the so-called hydrodynamic trend, which clearly does not correspond to the modern stage of hydrological science.

The presently active stationary system of hydrometric observation stations on rivers does not correspond to the requirements of studying ice jams. The full-scale data obtained by this system are extremely incomplete and disparate, and therefore it is extremely important in analyzing them to be governed by certain general principles regarding the essence of the process (1, 3, 4). Without this, conclusions may be random and even erroneous.

Ice jam formation is an obligatory component of the debacle process of many rivers. In the period from the time the ice cover achieves its maximum thickness over the Winter and before the beginning of the massive Spring debacle, two groups of factors are simultaneously active:

a) a gradual weakening of the ice cover under the effect of warm air and solar radiation, as well as the heat of melted snow water;

b) an increase in the tractive force of the water stream on the boundary of the water - ice interface resulting from an increase in the flow rate of water in the river.

For the sake of brevity, we shall term the first group of factors thermal factors and the second group of factors mechanical factors. Obviously, the break-up of the ice cover into individual masses and the break-up of the field will occur at the time when stress in the ice cover exceeds its strength limit.

The topographical, hydrometric and other materials needed in analyzing the process of ice jam formation on a river are extremely varied. Certainly, the most valuable ones are the frequent observations of water levels and ice phases on adjacent water monitoring station positions and the longitudinal profiles of the water surface of the river over characteristic moments in time plotted on their basis.

During the analysis of the indicated material for a number of rivers, one can draw certain important conclusions:

- one should distinguish locations of the annual formation of ice jams and stretches of the river with variable foci of ice jams which are inconstant and meander from year to year. As it is case now that forecasts are only possible for places where ice jams appear almost annually, if only because long-term observations of the water level made in the stationary water measuring system are indicative for them, then the following hold;

- as a rule, the location of the annual formation of ice jams tends toward the break in the longitudinal profile of the river from a stretch with a sharp slope (which means a rapid current) toward a stretch with a low slope (and consequently, with a slow current). Such stretches include the areas where reservoir abutments wedge into the stream, the mouths of rivers when they enter a sea or lake, areas of transition from rapids (semi-mountainous) stretches of rivers to plains. In some cases, the location of annual ice jam formation can be on a stretch of river where several types of channel obstacles are combined, for example, a sharp bend (over 110 - 120°) with an alluvial fan.

Applicable to the set task, one should also include stretches where the locations of ice jams are located a short distance apart among the stretches with nearly annual formation of ice jams with a known cause. Of course, the magnitude of the observed ice jam maximum at the water monitoring station will depend upon where, in fact, the ice jam has formed below the station in a given year, but this difference is not so important if one takes into account the entire value of the ice jam level increase and the fact of a noticeable drop in slope in the area of the abutment from the ice jam.

Ice jam formation is a multifactorial process in whose course the cause and effect frequently alternate. The existing concepts about the natural essence of the process of ice jam formation are incomplete. Current information about the basic factors of this process is inadequate. At present, in forecasting ice jams, one must first be satisfied with taking one or two integral indices of the process into account, and second, one must bear in mind the specific features of the aqueous and ice regimes of the river in the debacle period. The magnitude of the average flow rate of water Q_{av} at the edge of the ice cover along the path of its movement within limits of the ice collecting stretch (as the characteristic of mechanical factors of the process) can be an integral indicator for locations where the ice jams form annually or nearly annually. Another integral indicator is the strength of the ice cover at the time of river debacle σh_i, as the result of thermal factors (2).

We shall further make a number of partial remarks.

On ice-jammed rivers (stretches of rivers), the debacle front always propagates downstream. In the debacle process the mechanical factors predominate over the thermal factors. Consequently, one should pay chief attention to estimating the magnitude of flow rate Q_{av}.

The length of the ice collecting stretch is approximately found as a derivative of the average surface velocity of water flow over the duration of the period of the dense, and sometimes, average ice gang, more accurately, when at a given point the surface coverage of the river with floating ice diminishes from 1.0 to 0.3. The sparse ice gang subsequent to this on the river has already

nearly been universally due to the transport of ice from secondary streams and tirbutaries, the ice wash-out from shore build-ups during the rise in water level, etc.

The flow rate of water at the edge of the ice cover during movement of the ice down the river, of course, does not stay constant. Inasmuch as the high water moves more rapidly down the river than the debacle front, then the flow rate of water at the edge gradually increases both on the non-flow and, particularly, on the main stream stretch of the river. It is significant that the indicated average flow rate at the edge of the ice Q_{av} emerges as the direct and indirect characteristic of the process of ice jam formation.

The direct effect of the flow rate Q_{av} is quite obvious. The greater Q_{av}, then the higher the maximum ice jam level when all other conditions are equal. The flow rate increases with the increase in Q_{av}, which means that the forces which lead to hummocking, floes, layered ice, etc. grow stronger.

The indirect effect of flow rate Q_{av} is less obvious, but is also great. Thus, when the flow rate of water is high the debacle front advances downstream comparatively rapidly, without halts and ice dams. As the result, large masses of firm ice participate in the formation of the ice jam in locations where the ice jam occurs annually. When Qav is small, the edge of the ice cover advances slowly, with partial halts in locations of temporary ice jams. In such places a great deal of ice remains in jams on the shores. Small masses of weak ice approach the location of the annual formation of ice jams.

It is significant that both integral indices of the process of ice jam formation - flow rate Q_{av} and the destructive stress ch_i - are frequently interrelated. If in any given year the river has undergone debacle at a low level H_{deb} (consequently, at a low flow rate Q_{av}), then this means that ice cover was not stable, and, vice versa.

For confirmation, we refer to works (2, 9), whose authors suggest identifying empirical relationships of the type $\sigma h_1 \lessgtr f(H_{deb})$.

We shall assume that hydrographs of the Spring high water period have already been pre-calculated in some fashion for several stretches of the ice collecting region, for example, the upper, middle, and lower. We shall further assume that dates of the debacle in these stretches are known in advance. Then, by summarizing the flow rates in these stretches on the day of debacle and by averaging them, we obtain the value of the integral characteristic Q_{av}. The difficulties consist in the fact that presently there is no precise method of predicting the dates of a river's debacle, specifically on a dammed region. Furthermore, in the examined period the water levels in the river are distorted by the ice phenomena, which sharply reduces the accuracy of calculating flow. Finally, the course of the river debacle process to a great extent depends upon future weather conditions, which are known to the forecaster only within the most general outlines. For the reasons given above, unique methods of directly or indirectly estimating flow rate Q_{av} are used for each river, in addition to carefully taking into account the specific features of its water and ice regimes.

A description of local methods of forecasts of the ice dam maxima for certain rivers is given in the works of authors (5, 7). Here we shall limit ourselves solely to presenting general conclusions relevant to the accomplished work.

It follows from the purely fundamental concepts that the relationships for predicting the ice dam maxima of levels should only be identified for those years when ice dams were noticed. However, in this case it is necessary to introduce a criterion of whether or not there will be a dam. In a practical regard, it is more correct to use all years of observations (more accurately, all instances of debacle). If there was no ice dam, then one can accept, for example, the highest level over the period of the thick ice gang as the ice dam maximum.

When establishing local forecast relationships of the following type

$$H_{max.\ dam} = f(Q_{ave}), \tag{1}$$

primary significance attaches to choosing the moment of issuing the forecast. The unique feature consists in the fact that the indicated moment should be uniform from year to year both with respect to the water and ice regimes of the river.

On those rivers (stretches) where the high water wave runs in a transit, or where the edge of the ice cover always moves from upstream to downstream, it is simplest to weight the forecast issuance time to the day of debacle at the point of observations near the upper boundary of the ice collecting stretch. Flow rate Q_{av} is arbitrarily assumed to equal the total of $Q_{up} + Q_{lat}$. In order to increase the accuracy of determining flow rate in the upper stretch Q_{up} and flow rate of a lateral tributary Q_{lat}, one can put off issuing the forecast until later, for example, until the day the thick ice gang on the upper stretch terminates. A method of forecasting the maximum ice dam level of the Severnaya Dvina River near the city of Arkhangel'sk was devised according to the system described above (6).

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On rivers where the high waterway within the confines of the ice collecting stretch forms equally as the result of both the flow via the upper stretch of the sector and the lateral in-flow from the partial basin, it is convenient to wait the forecast release toward the time of onset of the maximum total of flow rates $(Q_{up} + Q_{la})_{max}$. An example can be the Dnestr River on the Mogilev-Podol'skiy-pgt Kamenka stretch (7). Characteristic for such stretches is the fact that in certain years the debacle occurs chiefly because of the flood from the partial basin. In this instance, the motion of the edge of the ice cover is accelerated and the timeliness of the forecast correspondingly drops.

There are rivers and river basins where the Spring flood on the ice collecting stretch forms by means of interference of the flood waves of individual rivers.
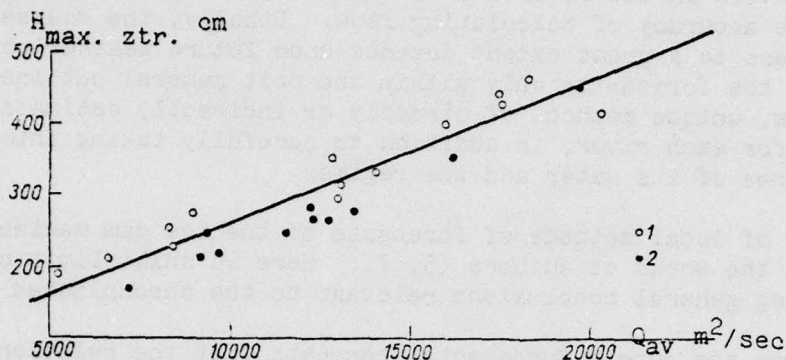

Figure 1. The relationship $H_{max.\ ztr} = f(Q_{av})$ for the Severnaya Dvina River
near the city of Arkhangel'sk.
1 - on the day of release of the forecast the edge of the ice cover is above the
Zvoz village; 2 - the same, below Zvoz village.

The debacle process occurs differently from year to year. The forecast release tends toward the time of peak onset of the flood on small rivers. According to the data on the distribution of water in the channel system (8) (or by other means), one calculates the course of water flow rates for the stretch in the middle part of the ice collecting part of the river. Then the calculated flow rates are averaged for a certain interval of time to the peak (usually, two or three days, including the peak day). The relationships $H_{max.\ ztr} = f(Q_{av})$ were obtained by the descriptive method for the Velika River near the city of Pskov (5) and for the Severnaya Dvina River near the city of Arkhangel'sk (Figure 1). We note that the selected moment for issuing the forecast is insufficiently homogeneous from year to year with respect to the ice situation. Therefore, one must additionally take into account, for example, the position of the debacle front or the strength of the ice cover on the day of compiling the forecast in the form of a third variable.

The solution to this problem for zones where the abutment of reservoirs wedges into the river, on the one hand, is chiefly complicated due to the varying pre-flood development, and, on the other hand, is facilitated because of the annual repetition of the phenomenon. The diagram of the solution to the problem is the following. One of the existing methods predicts flow rate

Q_{av}. For the condition of an open channel, a curve of the flow rate of water is established in the form of a function of three variables $Q(H, Z)$, where Z is the water level in the central part of the reservoir. According to the precalculated flow rate Q_{av} and the level Z_{ini} observed on the day of compiling the forecast with the aid of function $Q(H, Z)$, one finds the level according to the observation station in the area where the abutment wedges in which exists in the absence of an ice cover ($H_{Q_{av}}$, Z_{ini}). Finally, one constructs the following empirical relationship
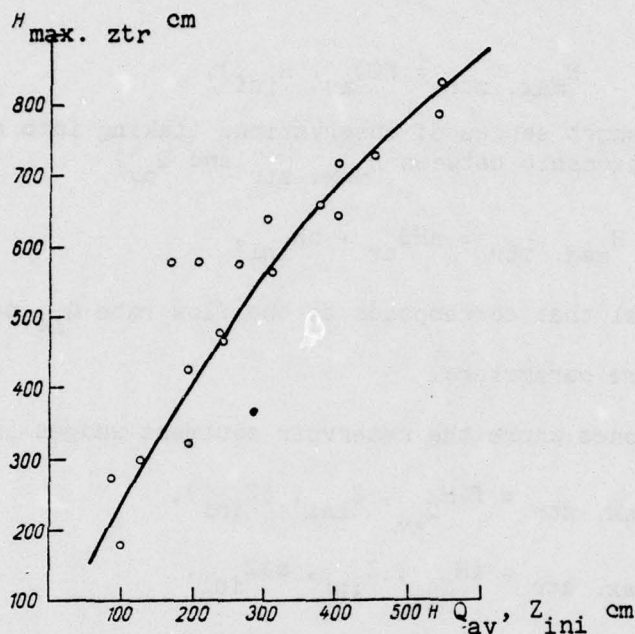
$$H_{max.\ ztr} = f(H_{Q_{av}}, Z_{ini}). \qquad (2)$$

Figure 2. The relationship $H_{max.\ ztr} = f(H_{Q_{av}}, Z_{ini})$ for the upper part of the

Kaunass reservoir near Birshtonas village.
The open circles show years when an ice neck existed near Birshtonas village at the time of forecast issuance.

For example, such a relationship was obtained for the area of abutment wedging of the Kaunass reservoir on the Neman River - Birshtonas village stretch (Figure 2).

In some cases, the magnitude of the anticipated level $H_{max.\ ztr}$ is significantly influenced by other factors that have still not been taken into account, primarily the residual Winter ice jams and cooling at the time of debacle.

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In regions with unstable Winter weather, the river freezes and thaws several times in certain years. The debacle usually does not encompass the entire river at the same time, but only a certain stretch of the river. In places where the debacle front has stabilized in Winter, ice barriers remain in the river channel on the shores. In freezing, they create additional obstacles to movement of the debacle front. At the location of the Winter residual ice jam the thickness of the Spring ice jam increases. One can approximately estimate the effect of the residual ice jam by the magnitude of the initial level at the point of observations H_{ini}, i.e., the level on the day of compiling the forecast. During this process, the forecast relationship will have the following form for the river in the case of the presence of an additional series of observations

$$H_{max.\ ztr} = f(Q_{av}, H_{ini}),\qquad(3)$$

and in the case of a short series of observations (taking into account non-linearity of the relationship between $H_{max.\ ztr}$ and Q_{av})

$$H_{max.\ ztr} = aHQ_{av} + bH_{ini},\qquad(4)$$

where $H_{Q_{av}}$ is the level that corresponds to the flow rate Q_{av} according to the curve $Q(h)$; a and b are parameters.

Similarly, for zones where the reservoir abutment wedges in,

$$H_{max.\ ztr} = f(H_{Q_{av}}, Z_{ini}, \delta Z_{ini}),\qquad(5)$$

$$H_{max.\ ztr} = aH_{Q_{av}}, Z_{ini}, b\delta Z_{ini},\qquad(6)$$

where δZ_{ini} is the drop along the length of the reservoir on the day of issuing the forecast (the level differential). In certain reservoir channels, the drop value δZ_{ini} itself, being a function of the flow rate Q and the mark of water level at the dam Z, fluctuates within quite significant limits. Having plotted the curve of flow rates $Q(H, Z)$ in the function $\delta Z = f(Q, Z)$, it is not difficult to obtain the value of drop according to the difference $\delta Z_{ini} - \tilde{\delta Z}_{ini}$ when necessary. This drop is due solely to the residual ice jam.

We note that prediction relationships of the type (4) have been established for the Dnestr River near Mogilev-Podol'skiy city and at the Kamenka pgt, while the type (6) has been established for the abutment wedging zone of the Dubossarsk reservoir (the cities of Rybnitsa and Rashkov).

The debacle of large rivers is a prolonged process during which cooling from an air temperature of -4, -6°C and lower can occur. The debacle gradually slows and then totally ceases because of front movement. In the halting point of the edge of the ice cover, the maximum ice jam level additionally rises (by 100 - 150 cm on the Dnestr and Neman Rivers, and can drop below this spot (by 50 - 100 cm).

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It is at present difficult to say where the debacle front will in fact halt.

Local methods of short-term forecasts of the ice jam maximum water levels have been developed for 11 stretches on four rivers (the Velikaya, the Neman, the Severnaya Dvina and the Dnestr). Investigations are being carried out on the low water reach of the Yenisey River (the Turukhansk-Ust'-Port stretch). Depending upon the size of the river and characteristics of its aqueous regime, the average timeliness of the forecast fluctuates from 1 - 2 to 6 - 8 days and the accuracy criterion $\frac{s}{\sigma_\Delta}$ ranges from 0.35 to 0.70.

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PREDICTING ICE JAM WATER LEVELS ON THE LENA RIVER

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Ice jam formation on the Lena River is a characteristic feature of the ice regime of this river. The thickness of the ice jams fluctuates from year to year and along the length of the river within broad limits (3, and others). The elevated ice jam frequency of the Lena River is due to the heterogeneity of ice thickness and to the change in morphometric conditions along the length of the river.

The wave of the Spring flood, in forming in the south of the river basin, moves downstream, encountering a more and more solid ice cover in its pathway. The ice cover is predominantly broken up under the mechanical action of the large mass of water.

The formation of ice jams on the Lena River tends toward certain locations - foci of ice jam formation - which are located, as a rule, on stretches that are characterized by reduced slope steepness (at the open stretch-rapids confluence), a sharp change in the direction of the channel or its fairway, by widening or construction of the main channel, as well as the appearance of channel formations - islands, shoals, bars, and holes. A change in channel morphology on any particular stretch of the river results in a sharp change in the flow velocity regime, and consequently, in the transporting capacity of the river. In this case the capacity of the river also changes, diminishing in places where the channel branches-off into a number of secondary streams and on stretches where there are sharp bends in the channel.

The flood wave, in washing against the river's ice cover, transports a large mass of ice to the ice jam formation focus, where the unbroken ice cover is usually preserved. On the approach to the focus of ice jam formation, the ice gradually fills the entire free surface of the water, after which the ice begins to pack and form layers. The most intensive ice fragmentation obviously occurs in that part of the channel where the greatest drop in levels is noted at that time and where the flow velocity has its maximum values. The increase in water level resulting from the head caused by the short-term reduction in ice packing continues simultaneously with accumulation of ice in the jam. This leads to ice advances into the jam. Still further ice packing occurs because of the advances of ice, the ice mass increases, the free cross-section of the channel builds-up into several layers. This causes an additional elevation in water level above the ice jam (3, and others).

The cited description of ice jam formation is not typical for the rivers of Yakutiya alone. In this regard, it is appropriate here to cite some general conclusions drawn by Ye. G. Popov which are specifically and fully applicable to the Lena River: "This obvious mechanism of development and autoliquidation of ice jams, within its general outline, actually represents in each specific case an exceptionally complex and theoretically unduplicatable system of interaction of forces and factors which it does not seem practically possible

to take into account". And further: "Various combinations introduce a significant element of chance into the locations of jam formation and the rising height of the level which they cause. The indicated circumstance deprives one in many cases of the possibility precisely to foresee these two important characteristics of the ice jam" (2). The random nature of the phenomenon worsens the inconstancy of the locations where ice jams form, a fact to which L. G. Shulyakovskiy paid attention in pointing out that "on a morphologically homogeneous stretch of a river, among the many stretches of transition from rapids to open waters, there are also others where the formation of an ice jam is equally probable because of hydraulic, morphological, and climatic conditions" (5).

A large number of foci of ice jam formation (about 180) have been identified on the Lena River (see the drawing), where Shulyakovskiy's referenced opinion is confirmed, as never before, with respect to the possibility of appearance of equally probable conditions for the formation of an ice jam in several foci of jam formation. Obviously, on the strength of this fact, the frequently observed movement of an ice jam from one focus to another also occurs with brief halts at any one of the aforementioned locations. If one takes into account that the distance between the identified foci of ice jam formation on the Lena River comprises an average of 20 - 25 km, and the length of the stretch of ice jam ice accumulation in the case of thick ice jams reaches 170 - 180 km, then the cause of the annually observed intensive rise in water level at the water monitoring stations during the river debacle becomes comprehensible.

Despite the fact that ice jam formation has been studied by many investigators, until now there have been no generally accepted schemes for calculating and forecasting ice jam levels. The merits and shortcomings of the different methods of determining the annual values of ice jam rises in water level have been examined in sufficient detail by M. A. Zhukova (1).

We shall point out that the maximum annual levels in the middle and lower course of the Lena River pertain to its debacle period. This makes it possible to consider both the ice jam maxima and the maximum levels homogeneous, i.e., those that are observed during the debacle, since the latter, like the ice jam, causes an additional rise in water level as the result of construction of the free river cross-sections by ice.

Analysis of observation materials obtained in the period of Lena River debacle demonstrated the possibility of using the water level immediately before the ice movement as an indirect characteristic of the readiness of the river's ice cover for debacle. It was noticeable that high water levels immediately before ice movement correspond to the best readiness of the ice for debacle and the thinnest condition of the formed jams. At precisely the same time, when water levels are low before ice movement on the Lena River, ice jams of varying thickness are possible:

   a) significant thickness, if the ice formed during high water and the Winter was a severe one;

   b) then, if the ice formed at a low water level and the Winter was a mild one.
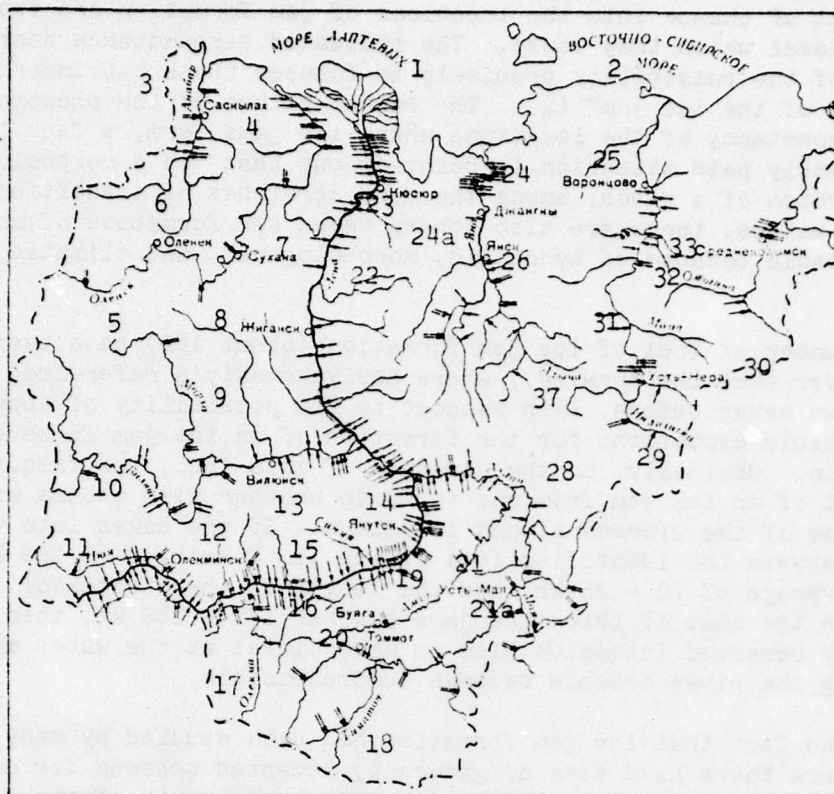
A map diagram of ice jam formation foci on the rivers of Yakutiya. 1 - ice jam
formation focus.

Key:

1 - the Laptev Sea
2 - the Eastern Siberian Sea
3 - Anabar
4 - Saskylakh
5 - Olensk
6 - Olenek
7 - Sukhana
8 - Zhigansk
9 - Markha
10 - Vilyuy
11 - Nyuya
12 - Olekminsk
13 - Vilyuysk
14 - Yakutsk
15 - Sinyaya
16 - Vuyaga
17 - Olekma
18 - Timpton

continuation of key for diagram on p. 92:

19 - Amga
20 - Tommot
21 - Ust'-Maya
21a - Maya
22 - Lena
23 - Kyusyur
24 - Dzhangky
24a - Yana
25 - Vorontsovo
26 - Yansk
27 - Adycha
28 - Aldan
29 - Indigirka
30 - Ust'-Nera
31 - Moma
32 - Ozhogina
33 - Srednekolymsk

It seemed possible to use the water level immediately before the ice movement as an indirect characteristic of the water level during this time and as an arbitrary reckoning measure during the determination of the ice jam rise in the water level. The ice jam level rises on the river Lena ΔH_z were calculated as the difference between the maximum ice jam level $H_{max.\ z}$ and the level immediately before ice movement $H_{H.\ p.}$.

With respect to the thickness of the ice jams, then the typification of ice jams (3), suggested before by the authors, was used as its characteristic. In accordance with this typification, an ice jam of the I type (the blind ice jam) is thickest. The moderately thick ice jam is of the II type (the dam-jam) and the thin one is an ice jam of the III type (the plug ice jam).

Each type of ice jam corresponds to a certain value of water level increase in the river, which is the greater, the thicker the ice jam. The excesses in maximum ice jam water level were divided into three gradations according to their magnitude: those with a frequency of less than 25%, those whose frequencies range from 25 to 75%, and those greater than 75%. It is conventionally assumed that ice jam level rises with a frequency of less than 25% are caused by I type jams; ice jams with a frequency ranging from 25 to 75% - II type jams, and those whose frequency is greater than 75% - III type jams. The average value ΔH_{av} has been calculated for each of these groups of ice jam water level rises.

The forecast of the highest ice jam water level is compiled after carrying out aviation reconnaissance of the ice condition of the Lena River in its debacle period. Having established the type of formed ice jam, one determines the possible magnitude of the highest ice jam water level at the closest water monitoring station by means of adding $H_{H.p}$ and ΔH_{av}. This pertains to the monitoring station located above the ice jam which corresponds to an ice jam of the established type.

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